Veneer Recovery Analysis of Plantation Eucalypt Species Using Spindleless Lathe Technology

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The Australian hardwood plantation industry is challenged to identify profitable markets for the sale of its wood fibre. The majority of the hardwood plantations already established in Australia have been managed for the production of pulpwood; however, interest exists to identify more profitable and value-added markets. As a consequence of a predominately pulpwood-focused management regime, this plantation resource contains a range of qualities and performance. Identifying alternative processing strategies and products that suit young plantation-grown hardwoods have proved challenging, with low product recoveries and/or unmarketable products as the outcome of many studies. Simple spindleless lathe technology was used to process 918 billets from six commercially important Australian hardwood species. The study has demonstrated that the production of rotary peeled veneer is an effective method for converting plantation hardwood trees. Recovery rates significantly higher than those reported for more traditional processing techniques (*e.g.,* sawmilling) were achieved. Veneer visually graded to industry standards exhibited favourable recoveries suitable for the manufacture of structural products.

Keywords: Eucalyptus; Veneer; Rotary veneer; Hardwood; Plantation; Processing; Grade quality; Recovery

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INTRODUCTION

The Australian timber industry, in particular the hardwood forest sector, is undergoing significant change. Much of this change results from reduced availability and/or reduced quality of the native forest resource for commercial harvesting purposes. Significant areas of native hardwood forests across Australia are being progressively withdrawn from commercial harvesting and managed principally for conservation purposes. While these challenges are not new on the global scene, Australian forestry is challenged with an accelerated transition from native forests to plantations.

About 84% of Australia's one million hectares of hardwood plantations has been established and managed for pulpwood production (Gavran 2013). Species selection, tree breeding programs, and plantation management have focused on achieving high pulp yield, targeted density, and maximum volume, which may adversely affect important properties for value-added solid wood products (Bailleres *et al.* 1995a,b; Bailleres *et al.* 1996a,b; Hamilton *et al.* 2010; Blackburn *et al.* 2011). Small areas of scattered plantations have been established for higher value products, mainly by State Government bodies. As a consequence, the hardwood plantation resource within Australia now consists of several species growing across a variety of climatic conditions and under a variety of management strategies, resulting in a wide range of plantation qualities and performances (Gavran 2013).

Recently, lower than expected product prices have resulted in an interest in higher value market options. This is despite site, species, and genetic selection, along with the lack of silvicultural inputs; for example, pruning and thinning are suboptimal for the production of logs suitable for many high value products.

Excluding high recovery rate processing technologies such as fibreboard or particleboard manufacture, previous processing studies of plantation eucalypt logs have focused mainly on conventional production systems to produce the traditional suite of sawn products (*e.g.*, Washusen 2011; Washusen and Harwood 2011; Blakemore *et al.* 2010a,b; Washusen *et al.* 2009; Leggate *et al.* 2000). This work has shown that difficulties are encountered in processing most of the existing hardwood plantation resources, with persistent problems arising in recovery, drying, stability, durability, and appearance qualities (Washusen *et al.* 2009). The result has been low profitability due to factors such as small log dimensions, high proportions of juvenile wood, growth stresses, and the high presence of knots. For example, Leggate *et al.* (2000) reported grade recoveries for a range of eucalypt species between 8% and 19% of log volume when sawn into commercial flooring products—less than half of what would be expected from mature native forest logs. Furthermore, Blackburn *et al.* (2011), in a sawing study of more than 500 *Eucalyptus nitens* plantation trees that used modern linear sawmilling technology purposely designed to maximise sawn-board recovery, showed that approximately half of the usual percentage recovery was possible.

Recent international advances in small log sawmilling, mainly tailored for the softwood industry, may have some application in the processing of plantation hardwoods. Nevertheless, challenges remain, including the economic impacts of high capital investment, large volume throughput requirements, low recovery of product, and the matching of dimensions and qualities of sawn wood to markets (Washusen 2011; Washusen and Harwood 2011). Other opportunities exist in the use of emerging thin-sawing techniques to produce attractive "overlays" for products such as composite flooring. This allows the unique properties of these hardwoods species, such as hardness and/or high aesthetic appeal, to be maximised. However, high costs of production, low recovery rates, competition from other more easily converted forest resources, and poorly established markets continue to make this approach economically challenging.

Preliminary research (Hopewell *et al.* 2008; McGavin *et al*. 2006) has shown that the conversion of plantation hardwood logs into veneer can yield significantly higher recoveries when compared with sawn timber processing. The resulting veneer is reported to have mechanical properties that are suitable for the manufacture of structural products (*e.g.*, plywood, laminated veneer lumber, *etc.*) in demand from the building industry (Hopewell *et al.* 2008). This processing method is not without challenges. Reliable adhesive performance and suitable technology to process small diameter logs are among a range of issues requiring further investigation.

While some preliminary research on plantation veneers has provided positive and encouraging results (*e.g.*, Hopewell *et al.* 2008 and McGavin *et al*. 2006), they remain reliant on the use of existing local industry-adopted processing and manufacturing technologies, most of which are not designed for or ideally suited to small-diameter fastgrown plantation hardwoods. New technologies that have emerged in recent years are better suited to this resource, giving the potential for greater recovery and improved quality. In particular, the use of spindleless or centreless veneer lathes has rapidly expanded, primarily for peeling small-diameter forest resources (Arnold *et al.* 2013). This technology was originally developed in the 1980s to further process the large peeler cores produced from spindled lathes. In more recent years, spindleless lathes have been further developed and adopted through many Asian countries for processing billets from very small diameter trees with success. According to Arnold *et al.* (2013), there are more than 5,000 small-scale veneer mills in China dedicated to the processing of young, small-diameter eucalypt logs. However, there are few publications providing detailed information on the veneer quality and recovery from spindleless lathe technology (*e.g.*, Luo *et al.* 2013). To date, there are no published recovery data (including product grade recovery) for the use of this technology in the processing of Australia's plantation resources, which involve different species and climates from those in Asian countries.

Arnold *et al.* (2013) reported that the adoption of this technology dramatically changed China's veneer processing industry because there is no longer the usual prerequisite for large diameter billets. Instead, small diameter logs (small end diameters of 6 cm or less) from plantations as young as 4 to 5 years old can be processed economically to yield high value veneer (Luo *et al.* 2013). A key to China's production success is the a large number of small-scale operations located close to the forest resource, each using equipment with a low capital cost and dependent on the availability of low-cost labor.

Using spindleless veneer lathe technology and best practice commercial processing methods, this study aimed to quantify and report on log and grade recoveries from logs harvested from six commercially important Australian hardwood plantation species grown for pulpwood and sawn timber.

EXPERIMENTAL

Plantation Sampling

Trees were sampled from commercial plantation stands representing the average resource currently available for the industry's use now and in the immediate future. Six of the major commercially important Australian plantation hardwood species were selected. The species included: *Corymbia citriodora* subsp. *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). Plantations sampled were established for a range of end products from traditional pulp to high quality solid wood. The diameter at breast height over bark (DBHOB) was measured for the selected trees. Trees were harvested and cross-cut to provide 1.3 m veneer billets. Each billet met the minimum form requirements including straightness (<40 mm sweep), a small end over bark diameter (SEDOB) no less than 120 mm, along with an absence of ramicorns, double leaders, major branches, and visible external injuries. The billets were sampled so that no more than five billets per tree were collected to ensure adequate representation of trees within the study. Table 1 provides a description for each species, age, plantation location, number, and the DBHOB of trees' sampled, and the number of billets included in the study.

Table 1. Plantation Trial Material

Species	Main Traditional Market	Age (years)	Plantation Location	Number of Trees	Average DBHOB * (cm)	Number of Billets
Corymbia citriodora subsp. *variegata*	Sawn timber	10–12	Urbenville, New South Wales (28°25′S, 152°32′E); Lismore, New South Wales (29°02′S, 153°05′E); and Tingoora, Queensland (26°22′S, 151°48′E).	80	20.6 (2.5)	215
Eucalyptus cloeziana	Sawn timber	12–15	Pomona, Queensland (26°23′S, 152°52′E); and Beerburrum, Queensland (26°23′S, 152°52′E).	55	31.9 (6.3)	223
Eucalyptus dunnii	Pulp and fibre	11	Urbenville, New South Wales (28°28′S, 152°35′E)	60	22.9 (3.5)	148
Eucalyptus pellita	Sawn timber	13	Ingham, Queensland (18°40′S, 146°8′E)	38	28.1 (4.3)	130
Eucalyptus nitens	Pulp and fibre	20–22	Strathblane, Tasmania (43°38′S, 146°94′E); Geeveston, Tasmania (43°15′S, 146°84′E); and Florentine, Tasmania (42°66′S, 146°47′E).	41	34.0 (7.4)	82
Eucalyptus globulus	Pulp and fibre	13–16	Deans Marsh, Victoria (38°39′S, 143°92′E); Orford, Victoria (38°21′S, 142°07′E); and Mumbannar, Victoria (37°96′S, 141°22′E).	60	30.6 (3.7)	120
* Standard deviation is presented in parentheses.						

Billet Assessment

The following parameters were measured on each billet prior to processing:

- Large end diameter under bark or *LEDUB* (m)—measured from the circumference with a diameter tape;
- Small end diameter under bark or *SEDUB* (m)—measured from the circumference with a diameter tape;
- Sweep or *S* (m)—measured as the maximum deviation from a straight edge that bridges the ends of the 1.3 m billets; and
- Shortest small end diameter or *SD* (m)—the shortest small end diameter was measured on the *Eucalyptus dunnii* and *Eucalyptus globulus* billets only using a steel rule.

An additional billet diameter was measured after each billet was rounded by the lathe. This process removed the minimum amount of the outer log required to prepare the billet for rotary peeling and veneer collection. The rounded diameter (*RD*) was measured from the circumference with a diameter tape.

From the measured data, the following parameters were derived for each billet,

$$V = \left(\frac{SEDUB + LEDUB}{2}\right)^2 \times \frac{\pi}{4} \times L \tag{1}$$

where V is the individual green billet volume (m^3), *SEDUB* and *LEDUB* are described above, π is 3.141593, and L is 1.3 m, the nominal length of the billet.

$$D_{CALC1} = SEDUB - S \tag{2}$$

In Eq. 2, D_{CALC1} is the geometrically calculated rounded billet diameter (m) that remains once the billet has been rounded to a cylinder in preparation for peeling, and *SEDUB* and *S* are as described above,

$$D_{CALC2} = SD - S \tag{3}$$

with D_{CALC2} equal to the geometrically calculated rounded billet diameter (m) that remains once the billet has been rounded to a cylinder in preparation for peeling, and where *SD* and *S* are as described above.

The methodology for calculating the rounded billet diameter based on simple geometrical considerations was developed to investigate its use as a straightforward predictive tool. The calculation was based on two easy-to-measure billet attributes; SEDUB and S. For *Eucalyptus dunnii* and *Eucalyptus globulus* billets, analysis using SD and S was also explored to investigate whether the correlation between actual and calculated rounded diameter could be improved with another easily measured log trait.

Billet Processing

Peeling was performed using an OMECO TR4 spindleless veneer lathe. The lathe has backup rollers with ganged teeth which are positioned by a combination of a mechanical and a hydraulic system. A mechanical drive system on the backup rollers turns the billet on the periphery, eliminating the need for traditional spindle mechanisms. The nose bar is a non-driven roller system. The lathe is capable of processing billets with a maximum length of 1,350 mm and maximum log diameter of 400 mm. The minimum peeler core size is 45 mm. The actual peeler core was measured on each billet. A small number of *Eucalyptus nitens* billets were too large (>400 mm) to process on the spindleless lathe. These were rounded and/or partially peeled using a conventional spindled lathe before the peeling was completed on the OMECO TR4 spindleless lathe. For the study, the nominal dried veneer thicknesses were 2.4 mm, 2.5 mm, and 3.0 mm. These were selected to represent the most common veneer thicknesses used for structural veneer-based products in Australia. The lathe was set and operated with best practice operations to provide optimum veneer quality. The majority of billets were preheated until the billet core reached an average of 75 °C using saturated steam prior to peeling.

Veneer Management

The resulting veneer ribbon had green veneer measurements collected and then sequentially clipped to sheets with a 1,400 mm maximum width. This target sheet size was chosen to provide 1,200 mm dried and trimmed veneer sheets as per standard industry practice. Veneers down to 300 mm wide were included, with the exception of a number of 150 mm wide sheets specifically targeted for veneer property evaluations (details not reported). While these 150 mm sheets were not specifically graded, a grade was assigned based on known neighbouring veneer qualities. Veneer sheets were labelled with a unique identifier and seasoned with a conventional jet box veneer drying system using standard commercial practises (temperatures ranged from 160 °C to 190 °C during drying) with a target moisture content of 5%. Veneers were then stabilised to 10% moisture content in storage.

The following parameters were measured on the veneer sheets:

- Green veneer thickness (*GT*)—the thickness of each green veneer sheet, measured using a dial thickness gauge (±0.01 mm) at three locations along the sheet length;
- Green width (*GW*)—the width (perpendicular to grain) was measured from green veneer sheets prior to clipping and excluded any major defects (*i.e.*, wane or undersize thickness) that was present at the beginning or end of the veneer ribbon;
- Dried veneer thickness (*DT*)—the thickness of each dried veneer sheet, measured using a dial thickness gauge at three locations along the sheet length; and
- Dried veneer width (*DW*)—the width (perpendicular to grain) of each dried veneer sheet.

Visual Grading

Veneer quality was assessed by visual grading in accordance with Australian and New Zealand Standard *AS/NZS 2269.0:2012* (Standards Australia 2012). This standard is widely adopted across the Australian veneer industry and follows the same principles as other international veneer visual grading classification systems. The standard separates structural veneer into four veneer surface qualities and a reject grade according to severity and concentration of imperfections and defects. The grading process was undertaken by a minimum of two experienced graders to minimise variation with defect definition and measurement and to ensure consistent assessment.

Recovery

Four recovery calculation methods were used, including green veneer recovery, gross veneer recovery, net veneer recovery, and graded veneer recovery. Green veneer recovery provides a useful measure of the maximum recovery, taking into account log geometry (sweep, taper, circularity) and lathe limitations (*e.g.*, peeler core size). Green veneer recovery disregards internal log quality. Green veneer recovery (*GNR* as %) was calculated as follows,

$$GNR = \left(\frac{L \times \sum_{veneer} (GT_{mean} \times GW)}{\sum_{billet} V}\right) \times 100 \tag{4}$$

where GT_{mean} is the average green veneer thickness (m) from all measurements taken from the individual trial, *GW* is the green veneer width (m, perpendicular to grain) as measured prior to clipping and excluding any major defects (*i.e.,* wane or undersize thickness) that were present at the beginning or end of the veneer ribbon, and *L* and V are as described for Eq. 1.

Gross veneer recovery provides a useful measure of the maximum recovery of dried veneer that meets the quality specifications of *AS/NZS 2269.0:2012* (A-grade to D-grade). This recovery includes the losses accounted for in green veneer recovery but also includes additional losses from visual grading (*i.e.,* veneer which failed to meet grade) and the drying process (*e.g.,* veneer shrinkage, splits, *etc.*). Gross veneer recovery (*GSR* as %) was calculated as follows,

$$GSR = \frac{L \times \sum_{veneer} (DT_{mean} \times GRW)}{\sum_{billet} V} \times 100 \tag{5}$$

where DT_{mean} is the mean dry veneer thickness (m) from all measurements taken from the individual trial, *GRW* is the width (m, perpendicular to grain) of dried veneer that meets the grade requirements of A, B, C, and D grades in accordance with *AS/NZS 2269.0:2012*, and *L* and V are as described for Eq. 1.

Net veneer recovery provides a useful measure of process efficiency, as it identifies the saleable product, taking into account the product manufacturing limitations. Net veneer recovery includes the losses accounted for in gross veneer recovery but also includes the additional losses due to the trimming of veneer before, during, and after product manufacture. The loss incurred when veneer sheets are reduced in width to the final product size is known as a trimming factor. In this study the trimming factor was 0.96, which corresponds to reducing the veneer sheet width perpendicular to the grain from 1,250 mm to 1,200 mm. The veneer sheet parallel to the grain was systematically reduced from 1,300 mm to 1,200 mm. Net veneer recovery (*NR* as %) was calculated as follows:

$$\begin{aligned} &NR = GSR \times 0.96 \times \frac{1200}{1300} \\ &thus\ \ NR = GSR \times 0.88615 \end{aligned} \tag{6}$$

Graded veneer recovery is the net veneer recovery for each grade as defined by *AS/NZS2269.0:2012* (*i.e.,* A, B, C, or D grades). Graded veneer recovery was calculated for each grade quality and is defined as NR_A, NR_B, NR_C, and NR_D.

Statistical Analysis

Analysis of variance and correlation coefficients were calculated to determine associations between the measured traits using IBM SPSS version 21. Pearson's product-moment correlation coefficients were calculated to determine associations between the measured traits. A single factor general linear model was fitted to the untransformed raw data for key variables to assess the difference between species (factors) based on all their billet's variables. *Post hoc* multiple comparison tests were performed through Tukey's Honestly Significant Difference Test. It uses the studentized range statistic to make all pairwise comparisons between groups and sets the experiment error rate to the error rate for the collection for all pairwise comparisons.

RESULTS AND DISCUSSION

A total of 918 billets from six different hardwood species totalling 48 m^3 were processed into rotary veneer. Table 2 provides details of the billet characteristics for each species.

Table 2. Billet Characteristics of the Six Hardwood Species

Species	Average Billet Small-end Diameter Under Bark (cm)	Average Billet Volume (m^3)	Total Volume Processed (m^3)	Average Sweep * (mm)
Corymbia citriodora subsp. *variegata*	15.6 (2.52)	0.028 (0.009)	5.936	11 (5.09)
Eucalyptus cloeziana	23.5 (5.23)	0.062 (0.027)	13.884	12 (6.98)
Eucalyptus dunnii	17.5 (3.31)	0.035 (0.014)	5.165	10 (5.20)
Eucalyptus pellita	20.9 (3.84)	0.049 (0.019)	6.354	11 (4.77)
Eucalyptus nitens	28.9 (7.09)	0.095 (0.052)	7.778	8 (4.33)
Eucalyptus globulus	25.7 (3.47)	0.072 (0.020)	8.659	11 (5.22)
* Rounded to nearest mm, standard deviation presented in parentheses				

The *Eucalyptus nitens* billets were sourced from the oldest plantations included in this study. *Eucalyptus nitens* billets had the largest average SEDUB and largest average billet volume of 28.9 cm and 0.095 m^3, respectively, but also displayed the largest variation ranging from 17.5 cm to 52.0 cm and 0.033 m^3 to 0.287 m^3, respectively. *Eucalyptus cloeziana* and *Eucalyptus globulus* billets had similar SEDUB characteristics, with averages of 23.5 cm and 25.7 cm, respectively. *Eucalyptus pellita* and *Eucalyptus dunnii* followed with an average SEDUB of 20.9 cm and 17.5 cm, respectively. *Corymbia citriodora* subsp. *variegata* displayed the lowest average SEDUB of 15.6 cm, and, as expected, the lowest average billet volume of 0.028 m^3. This species also displayed the least variation in SEDUB and billet volume, ranging from 9.5 cm to 22.5 cm and 0.01 m^3 and 0.06 m^3, respectively.

The analysis of variance performed on sweep by species showed significant differences between samples of these species. Table 3 displays homogeneous subsets for range tests from *post hoc* multiple comparison tests based on Tukey's Honestly Significant Difference Test. Most of the species exhibited similar billet sweep characteristics (average sweep between 10 and 12 mm), with the exception of *Eucalyptus nitens*, which displayed a significantly lower average billet sweep of 8 mm. This result suggests that, compared to the other species, *Eucalyptus nitens* has a natural tendency toward straightness.

Table 3. Sweep *Post Hoc* Multiple Comparison Tests based on Tukey's Honestly Significant Difference Test

Species	N	Subset		
		1	2	3
Eucalyptus nitens	70	7.6		
Eucalyptus dunnii	146		10.0	
Eucalyptus pellita	129		10.9	10.9
Eucalyptus globulus	120		11.0	11.0
Corymbia citriodora subsp *variegata*	213		11.4	11.4
Eucalyptus cloeziana	141			12.2
Means for groups in homogeneous subsets are displayed based on observed means. Alpha= 0.05.				

The green veneer recovery depends on the processing cutting pattern. The first step when peeling is rounding, the process whereby the billet is machined to a cylinder with consistent diameter and parallel sides. During this step, no usable veneer is recovered. Thus, in the peeling process, the green recovery depends on the ratio of volumes between a hollow cylinder (rounded billet excluding the peeler core) and an irregular truncated cone (billet). As a consequence, the parameters that impact the rounded billet size and therefore green recovery are primarily SEDUB, sweep, taper, and circularity.

Using billet SEDUB and sweep measurements to predict the billet rounded diameter (calculation method 1 or D_{CALC1}) has proven to be a relevant method with a strong correlation with r^2 values ranging between species from 0.86 to 0.98 when compared with the actual measured rounded billet diameter (Table 4).

Table 4. Coefficients of Determination between Calculated and Actual Measured Rounded Billet Diameter

Species	Calculation Method 1 (r^2)	Calculation Method 2 (r^2)
Corymbia citriodora subsp. *variegata*	0.93	-
Eucalyptus cloeziana	0.89	-
Eucalyptus dunnii	0.86	0.90
Eucalyptus pellita	0.95	-
Eucalyptus nitens	0.98	-
Eucalyptus globulus	0.87	0.91

Using the billet's shortest diameter (SD) instead of SEDUB, and sweep (calculation method 2 or D_{CALC2}) further improved the correlation for the two species that exhibited the lowest correlation using the first method. This improvement on the coefficient of determination was only 0.04 for both *Eucalyptus dunnii* and *Eucalyptus globulus*. Other factors such as billet surface irregularities (*e.g.*, flutes), which are also more difficult to measure, would only be expected to provide marginal improvements. With coefficient of determination at about 0.9, the unexplained variance is probably mostly due to the experimental measurement error. This indicates that while the second method does provide an improved prediction, either method could be used to predict the effect of billet form on green recovery. This has a range of potential applications including determining optimal billet grade thresholds and predicting the impact of changing billet length (*e.g.*, 1.3 m versus 2.6 m long billets).

The measured veneer recoveries are displayed in Table 5. All species achieved green veneer recoveries between 68% and 77%. *Eucalyptus globulus* achieved the highest green veneer recovery, while *Corymbia citriodora* subsp. *variegata* achieved the lowest. *Eucalyptus nitens*, *Eucalyptus pellita*, and *Eucalyptus cloeziana* each achieved recoveries within a close range (75% to 73%). *Eucalyptus dunnii* had a recovery (70%) between this group and *Corymbia citriodora* subsp. *variegata*.

Table 5. Veneer Recoveries

Species	Green Recovery (GNR as %)	Gross Recovery (GSR as %)	Gross Recovery Percentage of Green Recovery (%)	Net Recovery (NR as %)
Corymbia citriodora subsp. *variegata*	68	54	81	48
Eucalyptus cloeziana	73	65	88	58
Eucalyptus dunnii	70	62	89	55
Eucalyptus pellita	74	62	83	55
Eucalyptus nitens	75	62	84	55
Eucalyptus globulus	77	57	75	50

There was a strong correlation ($r^2 = 0.796$, n = 6) between species average SEDUB and green veneer recovery. This is understandable since SEDUB has been demonstrated to have a major influence governing the billet rounded diameter and therefore green veneer recovery. This was also observed by Thomas *et al.* (2009) in a study processing plantation eucalypt species within commercial facilities. The relationships that they determined were not as strong as those observed in the current study; however the recovery calculation methodology is not well-explained and may account for the weaker result.

Eucalyptus cloeziana yielded the highest gross and net veneer recoveries of 65% and 58%, respectively, followed by *Eucalyptus dunnii*, *Eucalyptus pellita*, and *Eucalyptus nitens*, which each produced gross and net recoveries of 62% and 55%, respectively. *Eucalyptus globulus* achieved 57% and 50%, respectively, while *Corymbia citriodora* subsp. *variegata* recorded the lowest gross and net recoveries (54% and 48%, respectively). Thomas *et al.* (2009) reported green off-lathe recoveries, which while not clearly defined, are assumed to be similar to gross veneer recovery, typically ranging from 35% to 45% for plantation *Eucalyptus dunnii* aged between 12 and 34 years. Similar recovery values are reported by Blakemore *et al.* (2010) for a small veneering trial processing 21-year-old *Eucalyptus nitens*. These values are quite low compared with this study, which could possibly be attributed to the application of traditional technologies, which produce larger diameter peeler cores and failed peeling due to spindle grip problems (*e.g.*, core splitting). In a study using spindleless lathe technology in China, Luo *et al.* (2013) reported an average green veneer recovery (defined similarly to gross veneer recovery in this study) of 44% (ranging from 28% to 51%) for 11 different five-year-old eucalypt clones. The comparatively low green veneer recovery observed is likely attributable to a lower average small-end diameter of the billets (112 mm).

To clearly separate the billet geometry variation between species from the internal billet qualities, the proportion of gross veneer volume recovered from the green volume has been calculated. *Eucalyptus globulus* produced the lowest proportion of gross veneer volume (75.2%), demonstrating that the samples of this species were most affected by defects preventing veneer sheets from being graded D-grade or higher. *Eucalyptus dunnii* was the least affected (88.8%), followed closely by *Eucalyptus cloeziana* (88.0%), then *Eucalyptus pellita* (83.5%), *Eucalyptus nitens* (83.5%), and *Corymbia citriodora* subsp. *variegata* (80.7%).

The analysis of variance performed on the proportion of recovered gross volume from the recovered green volume by species showed significant differences among species. Table 6 displays homogeneous subsets for range tests from *post hoc* multiple comparison tests based on Tukey's Honestly Significant Difference Test. Interestingly, the best and worst species were both traditional pulp species. *Eucalyptus dunnii* veneer did contain a large presence of imperfections, but they did not have a major impact on the recovery of gross veneer. For example, most veneer sheets contained many knots; however they were generally sound, small in size, and scattered, which resulted in minimal impact when graded. Similarly, *Eucalyptus globulus* veneer contained similar kinds of imperfections, although of much higher frequency and size.

Table 6. Percentage of Gross Veneer Recovered from Green Veneer *Post Hoc* Multiple Comparison Tests based on Tukey's Honestly Significant Difference Test

Species	N	Subset (%)			
		1	2	3	4
Eucalyptus globulus	120	75.2			
Corymbia citriodora subsp. *variegata*	215		80.7		
Eucalyptus pellita	130		82.8		
Eucalyptus nitens	82		83.5	83.5	
Eucalyptus cloeziana	219			88.0	88.0
Eucalyptus dunnii	166				88.8
Means for groups in homogeneous subsets are displayed based on observed means. Alpha= 0.05.					

These reported recoveries are high when compared with traditional sawmilling practices. The green veneer recoveries measured about twice the comparable recoveries for processing similar plantation resources using traditional sawmilling techniques (green-off-saw recovery, GOS). For example, Leggate *et al.* (2000) reported the green-off-saw recovering for solid wood processing (*i.e.*, sawmilling) of six hardwood *Eucalyptus* sp. at six Queensland plantation sites aged between 21 and 41 years as between 32.3% and 42.9%. The researchers also reported net grade recoveries from the same study for flooring type products of between 8% and 19%. This suggests that rotary veneer processing has the potential to recover up to six times the volume of saleable product from young plantation species when compared with traditional sawmilling techniques.

Across all species, the recoveries were dominated by D-grade veneer (Table 7). While some species did produce a small amount of A-grade veneer, the recoveries were considered insignificant (<1%). *Eucalyptus nitens* produced the highest percentage of B-grade recovery at 5%, which accounted for 9% of the veneer produced for this species. This was followed by *Eucalyptus cloeziana*, which produced a B-grade recovery of 2.8%. The samples of no other species produced any significant recovery of B-grade quality veneer (>1%). All species produced some C-grade veneer, with *Eucalyptus cloeziana* achieving a remarkable 15.7%, which accounted for 27% of the total volume of veneer for this species. The sampled *Corymbia citriodora* subsp. *variegata, Eucalyptus pellita*, and *Eucalyptus nitens* also produced in excess of 10% of the recovered volume of veneer as C-grade quality. Ninety-seven percent of *Eucalyptus globulus* veneer was D-grade.

Table 7. Graded Veneer Recoveries

Species	A-grade Recovery (%)	B-grade Recovery (%)	C-grade Recovery (%)	D-grade Recovery (%)
Corymbia citriodora subsp. *variegata*	0.2 (0.3)	0.5 (1.0)	7.9 (16.4)	39.6 (82.3)
Eucalyptus cloeziana	0.1 (0.2)	2.8 (4.8)	15.7 (27.1)	39.4 (68.0)
Eucalyptus dunnii	0	0	4.2 (7.7)	50.5 (91.9)
Eucalyptus pellita	0	0.8 (1.5)	5.7 (10.4)	48.2 (88.1)
Eucalyptus nitens	0.2 (0.4)	5.0 (9.1)	7.5 (13.7)	42.1 (76.9)
Eucalyptus globulus	0	0.4 (0.9)	1.2 (2.3)	48.8 (96.8)
* Recovered grade veneer as a proportion of net veneer volume is presented in parentheses.				

While D-grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core veneers for most appearance and non-appearance structural panels. The low recovery of higher grade veneers (C-grade and better), which are more suitable for face veneers, would make the commercial production of a standard mix of structural panel products challenging when only using a resource of this quality. According to the Engineered Wood Products Association of Australasia (EWPAA, www.ewp.asn.au), the Australian rotary veneer industry requires approximately 30% to 40% of their veneer production to be C-grade or better to enable saleable product manufacture. *Eucalyptus cloeziana* is the only species in this target range, with 32% of veneers produced being C-grade or better. This is followed by *Eucalyptus nitens* (23%), *Corymbia citriodora* subsp. *variegata* (18%), *Eucalyptus pellita* (12%), *Eucalyptus dunnii* (8%), and finally *Eucalyptus globulus* (3%). The blending of plantation hardwoods with higher quality veneers from native forest hardwoods or plantation (softwood or higher quality hardwood) resources may produce a more suitable quality mix.

CONCLUSIONS

1. The study demonstrated that processing representative stands of the current Australian hardwood plantation estate using spindleless veneer lathe technology can overcome many of the problems present when using traditional solid wood processing techniques. Green and gross recoveries achieved during the study were between 68% and 77% and 54% and 65%, respectively. These results are on the order of two to six times what is usually achieved from processing similar resources using traditional solid wood processing systems, presenting an opportunity to process plantation logs of younger ages and of lower quality. The observed differences between species reflect the performances of the plantation resource currently available. These results confound inherent differences between species with silviculture and age effects. Alternative forest management strategies with a focus on veneer products would be expected to improve their performances.
2. The graded veneer recovery was dominated by D-grade veneer across all species. While D-grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core veneers for the vast majority of appearance and non-appearance structural panels. The low recovery of higher grade veneers (C-grade and better) in the studied samples of all species, except possibly *Eucalyptus cloeziana*, would make the commercial production of structural panel products challenging (because of insufficient quantities of face veneer) if a processor were relying solely on this grade of resource. However, the blending of plantation hardwood veneer with higher appearance grade veneer may produce a suitable mix for a range of solid wood end products.
3. Predicting the billet's rounded diameter using easy-to-measure billet form characteristics (small-end diameter under bark or shortest small-end diameter and sweep) was demonstrated to be a satisfactory tool with a coefficient of determination between 0.86 and 0.98. This indicates that this approach could be used to predict the effect of billet form on green recovery and has a range of potential applications, including determining optimal billet grade thresholds and predicting the impact of changing billet length (*e.g.*, 1.3 m versus 2.6 m billets).

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