ANALYSIS OF SMALL-LOG PROCESSING TO ACHIEVE STRUCTURAL VENEER FROM JUVENILE HARDWOOD PLANTATIONS

Robert Lee McGavin
orcid.org/0000-0003-3143-9326

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The University of Melbourne

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ABSTRACT

The majority of the hardwood plantation estate in Australia has been established and managed for pulpwood markets; however interest exists from both forest and wood processing industries as to whether the resource could be processed into higher value products. This situation is consistent with many other countries where hardwood plantations have been established.

Previous wood qualities studies have confirmed that relatively young, fast-grown hardwood trees contain wood properties that are different from wood recovered from the same species which was sourced from mature, native forest trees. Despite this difference, the properties are generally in the range of desirable properties for many processing options and high-value end-products. Indeed, the reduction of some properties (e.g. density) may prove advantageous for some processes and end-products. Previous studies have also confirmed a large variation of properties within plantation trees as a result of the high proportion of wood which is formed in the juvenile phase of tree growth. Plantation trees are also known to yield relatively small diameter logs that contain a range of defects that affect the efficiency of processing methods and suitability for end-products.

Sawmilling and veneer processing are attractive processing options for production of value-added products. Many processing studies have been previously completed to convert plantation hardwood logs into a traditional suite of sawn products, mainly using conventional production systems. The results of these studies have consistently shown
that complications are encountered with persistent problems arising in recovery, drying, stability, durability and appearance qualities.

Rotary veneer processing has the advantages of yielding significantly higher recoveries when compared with sawn timber processing and the relatively small piece size (mainly in thickness) can reduce some of the effects of properties gradients and growth stresses; and reduce lengthy and problematic drying. Difficulties exist however in utilising traditional veneer processing methods for processing plantation hardwoods, especially where log diameters are small and end-splitting is common. A relatively newly developed veneer processing method can remove the difficulties experienced when traditional methods are used.

The objective of this PhD study was to analyse small-log processing through the application of lean spindleless rotary veneer processing methods to achieve rotary veneer for structural purposes from Australian-grown, juvenile hardwood plantations.

Simple spindleless lathe technology was used to process 918 billets from six commercially important Australian hardwood species (*Corymbia citriodora* subsp. *variegata*, *Eucalyptus cloeziana*, *E. dunnii*, *E. pellita*, *E. nitens* and *E. globulus*). 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. Recoveries achieved during the study were in the order of two to six times what is usually achieved from processing similar resources using traditional solid wood processing systems. The graded veneer recovery was dominated by D-grade veneer, the
lowest visual grade quality for structural veneer meaning the veneer is 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 veneers contained a range of defects that impacted the final assigned grade. The
presence of gum pockets, bark pockets and decay (mainly surrounding knots), encased
knots, splits and surface roughness were identified as the main defects limiting veneer
grades to D-grade, with other defects contributing to a lesser degree. Several scenarios
were simulated including a relatively easy change to the grading standard rules for gum
defects, and various outcomes resulting from the modelling of effective pruning. All
scenarios demonstrated a positive outcome with veneer values increasing by up to
nearly 23%.

Variation in veneer and grade recoveries was found within species growing across
different conditions and with different silvicultural treatments (thinning and pruning).
The results however were not consistent, especially when resulting veneer value was
assessed. While thinning and pruning is a common practise to target increased
production of higher-value clear wood, the study demonstrated that clear wood is not
always achieved which can result in a reduced veneer value.

Veneer density, dynamic modulus of elasticity (MoE) and specific MoE evaluations
revealed a wide variation of properties existed between species, within species and
within a billet. Veneer density was found to not always be a good predictor of MoE,
especially in commercial size samples which contain natural defects. Simple
mathematical modelling, 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.

Rotary veneer processing using spindleless lathe methods was shown to be able to efficiently process young, fast grown hardwood plantation trees with resulting veneers containing visual grade qualities and mechanical properties suitable for the manufacture of structural veneer-based products. Further research is necessary to determine appropriate end-products and optimised product manufacturing protocols. An economic evaluation is necessary to determine the potential profitability.
DECLARATION

This is to certify that:

i. The thesis comprises only my original work.

ii. Due acknowledgement has been made in the text to all other material used.

iii. The thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Robert Lee McGavin
PREFACE

This PhD thesis contains six chapters of which Chapters 2, 3, 4 and 5 have been published as peer-reviewed journal articles. The major research of these publications was carried out independently with the co-authors’ contribution in the form of supervision from experimental design to manuscript writing.

The citations of the published peer-reviewed publications are as follows:

Chapter 2


Chapter 3


Chapter 4


Chapter 5

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CHAPTER 1

1.1 Background and literature review

Worldwide, there are 264 million hectares of planted forest which represents about 7% of the world’s total forest area (Overbeek et al. 2012). FAO (2010) reports that about three quarters of these plantings are grown for productive purposes such as wood, fibre and fuel. The establishment of industrial scale plantations is a relatively recent phenomenon which gained significant momentum since the 1960’s (Overbeek et al. 2012). For example, the planted forest estate in the southern hemisphere is reported by Overbeek et al. (2012) to have increased from 95 million to 153 million hectares between 1990 and 2010. With the rapid expansion in planted forests and a decline in the harvesting of indigenous forest, planted forests are expected to play a significant role in supplying timber to the forest products industry into the future (FAO, 2010). China has the largest plantation area with 77 million hectares, followed by United States of America (25 million hectares), Russian Federation (17 million hectares) and Japan and India each with just over 10 million hectares (Jürgensen et al. 2014).

Softwood species account for 52% of the worldwide plantings while 37% are hardwoods (FAO, 2010). The balance is unspecified species. A well-established softwood processing industry exists which successfully processes the plantation softwood resource into a range of products including fibre for pulp and paper, fibre board products (e.g. MDF and particleboard), solid wood and engineered wood products.
Established hardwood plantations are made up of many different species however are dominated by the *Eucalyptus*, *Acacia*, *Tectona* and *Populus* genus. Eucalypt plantations account for just over 20 million hectares of the international hardwood plantation estate (GIT, 2009). The majority of these plantations were established for fibre products although there is increasing interest in using this resource for higher value products (Shield 2003, Montagu *et al.* 2003, Nolan *et al.* 2005).

Gavran (2012) reports that the Australian plantation estate in 2010-11 totalled 2.017 million hectares, of which 1.025 million hectares was softwood plantation, 0.980 million hectares was hardwood plantation with the remaining small area made up of mixed species plantings. Western Australia is reported to have 31% of the Australia’s hardwood plantation area, followed by Tasmania (24%), Victoria (21%), New South Wales (9%) and South Australia (6%). Queensland and Northern Territory each have 4% of the Australia’s plantation area (ABARES 2013).

While on a global scale Australia’s hardwood plantation estate is relatively small, it is potentially quite unique in that it is represented by climatic conditions that range from temperate through to tropical environments. The Australian plantation hardwood estate is also characterised by a diverse mix of planted species that range from those traditionally favoured for fibre products (e.g. *E. globulus, E. nitens* and *E. dunnii*) through to species with a strong history in solid wood utilisation (e.g. *C. citriodora, E. cloeziana* and *E. pellita*). In 2010-11, southern blue gum (*Eucalyptus globulus*) and shining gum (*E. nitens*) accounted for the majority of Australia’s hardwood plantations with 55.1% and 24.1% of the plantation area respectively (Gavran, 2012).
About 84% of Australia’s one million hectares of hardwood plantations have been established and managed for pulpwood production (Gavran, 2013). Species selection, tree breeding programs, and plantation management have largely focused on achieving high pulp yield, targeted density, and maximum volume, which may adversely affect important properties for more value-added wood products (Bailleres et al. 1995a,b; Bailleres et al. 1996a,b; Hamilton et al. 2010; Blackburn et al. 2011).

Despite the original plantation establishment and management intent, fluctuating and often unfavourable market conditions for pulpwood combined with a continuous desire from plantation growers to seek higher returns, have prompted the exploration of alternative higher value markets. At the same time, significant areas of Australian native forest are being progressively withdrawn from commercial harvesting and managed principally for conservation purposes. With the hardwood processing sector predominately reliant on native forest resources for log supply, the increasing limitations preventing access to some native forest areas, as well as the increasing availability of maturing hardwood plantations, interest is growing from the processor sector as to the suitability of the plantation hardwood resource for value-added products.

Small areas of scattered plantations have been established in Australia for higher value products, mainly by State Government bodies. Wood et al. (2009) reported approximately 26,000 hectares of plantations principally located in Tasmania, which are predominantly *E. nitens* plantations that have been thinned, pruned, and managed for higher-value end-uses.
Young-fast grown hardwood plantations yield relatively small diameter logs that can contain a range of defects that can be in high frequency. Example of the defects include spiral grain, growth stresses, knots, limited heartwood durability, kino veins and pockets, brittle heart and tension wood (Shield 2003). Defects such as these influence the efficiency of processing methods and suitability for end-products.

The wood properties of plantation wood differ markedly from mature native forest sourced wood (McLean et al. 2011). Basically, the initial fast growing conditions promoted generally by efficient silvicultural regimes, dramatically enlarge the volume of wood formed in the juvenile phase of the tree. In fact, the wood properties radial variations are mainly driven by the ontogenetic maturation of the cambium, which evolve progressively from a development phase of flexible and reactive characteristics to a state of stiffer and more stable characteristics. This juvenile wood phase, which is characterised by a large gradient of wood properties controlled essentially by the cambial age, thus related to radial growth, displays performances which are generally highly variable and technologically inferior to mature wood properties (Zobel and van Buijtenen 1989; Downes et al. 1997; Zobel and Sprague 1998). Many standard wood quality studies have been reported for Australian grown plantation hardwoods that provide the values for wood properties such as densities (basic and air-dry), modulus of elasticity (MoE), hardness, shrinkage and unit shrinkage rates (e.g. Ozarska and Ashley 1998, Leggate et al. 2000, Muneri and Leggate 2000, McGavin et al. 2006, McGavin and Bailleres 2007, Bailleres et al. 2008, Ozarska 2009, Harding et al. 2012, Downes et al. 2014).
Numerous studies have also confirmed the findings reported by Zobel and van Buijtenen (1989), with the identification of large variation in properties within plantation trees. For example, Downes et al. (1997), McGavin et al. (2006), Bailleres et al. (2008), Washusen et al. (2008) and Downes et al. (2014) each describe the radial increase of properties such as density. The methodology to measure the radial variability has mainly been based on fixed size of samples taken at regular intervals along the radius of the tree. These intervals have usually only provided limited data points across the radius such as to represent sapwood, outer heartwood and inner heartwood measure. These broad categories have resulted in a lack of true understanding of the evolution of key properties such as density and MoE as young trees grow and transition from juvenile to mature wood. Other studies provide a very fine description of these variations based on anatomical characteristics as reported by Wimmer et al. (2002), Washusen et al. (2005), Medhurt et al. (2012) and Downes et al. (2014) etc., however the scale has been generally too small to inform directly and usefully the technological properties required to connect to the product description. These studies also limit the understanding of how the variation of many wood properties in trees can be recovered during processing into products such as sawn wood or rotary veneer.

A large range of wood properties studies have confirmed that the plantation hardwood resources are different from the native forest hardwood resources that the industry is used to managing and processing. However, in general, the properties that the plantation wood displayed are generally within the ranges of desirable properties for many processing options and high-value end-products. For example, McGavin et al. (2006) reported an average basic density of around 600 kg/m\(^3\) for three plantations species (\textit{E.}
E. cloeziana, E. pilularis and E. pellita) each less than 10 years of age. While this is around 30% lower than the density expected from mature native forest wood of these species, it remains within the density range of most high volume timbers traded internationally. Indeed, the reduced density may prove advantageous for some processes and end-products.

There are different processing options available for targeting high-value wood products from hardwood plantations. However, sawmilling to produce solid wood products and rotary veneer processing for the manufacture of veneer-based composite products are preferred options by the industry due to reasonably easy to access markets and manageable scales of operation. FAO (2014) reports strong growth in the production and consumption of wood-based panel products and sawn timber with global production in 2013 increasing by 8% and 5% respectively. Only very modest growth (<1% per year) is reported for pulp and paper over the period 2009-13.

Many processing studies have been completed to convert plantation hardwood trees into a traditional suite of sawn products, mainly using conventional production systems both in Australia (e.g., Leggate et al. 2000; Washusen et al. 2008; Washusen et al. 2009, Blakemore et al. 2010a and b, Washusen 2011, Washusen and Harwood 2011) and outside Australia (e.g. Vermaas 2000, Malan 2000, Menezzi 2001, McKenzie 2003, XiMing et al. 2003, Ye 2003, Satchell and Turner 2010). The results of these studies have consistently shown that complications are encountered with persistent problems arising in recovery, drying, stability, durability and appearance qualities.
Recoveries are low due to losses that occur in converting round logs to square sawn boards and recoveries are reduced further as the log diameter decreases (cutting fixed size parallelepipeds from a conical shape). Recovery of green, ungraded boards from young plantation grown logs is typically around 30-40\% (Leggate et al. 2000). The presence of end-splits and distortions induced by the release of growth stresses during processing negatively impacts recovery (Leggate et al. 2000, Yang 2005, Washusen et al. 2008). The high frequency of knots and other defects which are common in young plantation trees further reduces recovery during product grading. Moreover, sawing techniques involve the generation of chips and saw dust at each processing step which systematically reduces the product recovery. Leggate et al. (2000) for example, reported grade recoveries for a range of plantation-grown eucalypt species of 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) conducted a sawing study of more than 500 trees of E. nitens plantation that used modern linear sawmilling technology purposely designed to maximise sawn-board recovery, which showed that approximately half of the usual percentage recovery was possible.

Plantation wood can be more difficult to dry with drying defects such as collapse, checking and distortion being frequently encountered (Washusen et al. 2000, Redman and McGavin 2010). In addition, sawing systems are not able to maximise the recovery of the outer log zones which contain the more attractive properties (e.g. higher density and MoE) and better grade qualities due to less defects (knots). The cross-section of the resulting sawn timber can be affected by large gradients of properties that help explain
the board distortions commonly experienced during sawing trials (e.g. Leggate et al. 2000; Washusen 2011).

Recent international advances in small log sawmilling, mainly tailored for the softwood industry and often targeting higher production speeds, may have some application in the processing of plantation hardwoods, however the fundamental approach to sawmilling essentially remains unchanged for centuries. The interaction between fast grown trees and small-diameter logs (generally < 30-40 cm) which are generally prone to high level of growth stresses and related reaction wood (thus have a high propensity to end split and/or to distort combined with steep gradients of properties), leads to a low recovery of marketable product and challenges in matching dimensions and expected qualities even through the most advanced sawing systems (Washusen, 2011; Washusen and Harwood, 2011). Advanced sawing systems are further challenged by high capital investment and large volume throughput requirements.

Other opportunities exist in the use of emerging thin-sawing techniques, such as high tension frame saws, 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. The relatively small piece size (mainly in thickness) can reduce some of the effects of properties gradients, growth stresses and resulting board distortions (e.g. spring and bow); and reduce lengthy and problematic wood drying (Blakemore et al. 2010b). 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.
Veneer processing takes the advantages of thin-sawing techniques however can yield significantly higher recoveries when compared with sawn timber processing (e.g. McGavin et al. 2006; Hopewell et al. 2008; Thomas et al. 2009; Farrell et al. 2011). This is largely because the peeling process is based on a cutting technique (with no chip or saw dust) that produces less off-cuts due to the absence of losses resulting from cutting square sections from circular logs. In addition, the veneering process removes wood from the log in a constant thin layer following a tangential spiral, which both contribute to dramatically limiting the gradients of properties within each veneer. Additionally, the rotary veneer process is much more efficient at recovering the wood from the log periphery which has more attractive qualities, and can be dried quickly with limited related degrades. Veneering essentially allows the log to be deconstructed with minimal waste, dried in small thickness dimension with relative ease, before being reconstructed using production strategies targeted to better utilise the available wood performances in product designs that better suits the end-use.

The traditional method of rotary veneer production uses a spindled lathe (Figure 1). This type of lathe uses spindles (or chucks) to hold the ends of a log (also referred to a billet or bolt) in position and to rotate it against a knife that is positioned parallel to the grain (Figure 2). A continuous ribbon of veneer, usually between 1–4 mm is produced from the billet periphery (Figure 3). In close proximity to the knife is a nose bar (or pressure bar) which applies a localised zone of compression just prior to the point of cutting that helps improve veneer quality. This method has proved to be a reliable and an effective way to produce high quality veneer, even at very high production speeds.
Figure 1. Traditional spindled veneer lathe

Figure 2. Spindle used to position and rotate a billet in a traditional veneer lathe.
When using spindled lathes, the billet is reduced in diameter during peeling to a size that is just larger than the spindles. Stopping at this point is necessary to prevent damage resulting from the knife coming into contact with the spindles. Historically, spindle size was large to facilitate the transfer of the torque forces necessary to hold and turn large diameter billets. Peeler core diameters in the range of 200 mm or greater were common from early model commercial lathes. The impact of this design was a large volume of the billet, in the form of a peeler core, which didn’t produce any veneer. For this reason, this processing method was more suited to larger diameter logs.

While spindled lathes have advanced considerably in recent decades, with improvements in reducing the peeler core size, optimised spindle positioning and faster production speeds; many of the developments have been designed to improve the efficiency of processing softwood resources.
Using spindled lathes for processing any hardwood resources has proven to present many challenges (e.g. Hopewell et al. 2008, Thomas et al. 2009). While the efforts to reduce the spindle size were made to improve the recovery of veneer, sufficient size is necessary to provide adequate billet holding capacity, especially during the early stages of peeling when billets diameters are largest. Failure to provide sufficient holding capacity leads to ‘spin outs’ where the spindles lose grip on the billet and the billet cannot be peeled further. Due to their generally higher density compared to softwoods, the level of forces generated when peeling hardwoods has meant that the opportunities to make substantial reductions in spindle size is limited. To compensate for smaller size spindles, spindle pressure can be increased meaning the spindles are forced more into the billet ends to achieve a better grip however billet end-splitting commonly results, especially in hardwoods (Figure 4). End-splitting which is a commonly reported occurrence for plantation hardwood logs further limits the success of spindle positioning and loading. In addition to these technical challenges, spindle lathe advancements have resulted in equipment that incorporate complicated and complex designs; and are often large capital investments.
Several veneer processing studies have been undertaken within Australia to process hardwood plantation billets. However these have been limited in size, sample replication and scope. In addition, these trials have utilised existing local industry-adopted processing and manufacturing technologies with normal production settings, which are not designed for or ideally suited to small-diameter fast-grown plantation hardwoods. For example, McGavin et al. (2006) reported on the veneer processing of 8.5 year-old red mahogany (*E. pellita*) in a project aimed at investigating a wide range of processing options for young plantation hardwood trees. While the trials were reported to have produced satisfactory structural plywood panels, the veneer trials were limited to only four billets with processing undertaken on a 1.3 metre spindled lathe using normal production settings. The industry partner that undertook the processing is an experienced processor of native forest eucalypt veneer however had limited experience in processing young plantation hardwood logs.
Hopewell et al. (2008) also reported a veneer processing study undertaken on 15 year-old red mahogany (*E. pellita*) and 19 year-old Gympie messmate (*E. cloeziana*). This study utilised limited resource with only 14 and 12 billets respectively and processing was undertaken in the same commercial operation as the study detailed above. Resulting veneer was visually graded, laboratory adhesive trials conducted, plywood panels were manufactured and basic mechanical properties were determined. The report provided some encouragement with gross veneer recoveries of 41% and 52% respectively for the two species and panel structural stress grades of between F14 and F27\(^1\) were achieved (suitable for high grade structural plywood).

Thomas et al. (2009) reported on the recovery and grade qualities of veneer produced from eight different eucalypt plantation areas covering five different species. Each species was represented with a plantation age of 34 years-old while one of the species was represented by a 12 year-old and 17 year-old planting. The study was conducted in the same commercial plywood mill as the two previously discussed studies under similar conditions. The report highlighted favourable strength properties however identified adhesive bonding issues, billet end splitting problems and billet ‘spin out’ during peeling. Limited detail was reported on veneer qualities and the variability of qualities that was produced.

Farrell et al. 2011 reported on a large scale veneer processing trial of predominantly plantation grown *E. nitens* and *E. globulus*. Veneer recoveries were recorded at around

\(^1\) The F-grade stress grading system is a method of classifying timber products for structural purposes.
50% however the grade recoveries were dominated by very low grade veneers when graded to the commercial grading standards. While detailed defect information was not provided, veneer checking and splitting was identified as a contributing factor for reduced veneer and product qualities.

Blakemore et al. 2010b reported the results of a preliminary veneer processing trial with an objective of comparing veneer recoveries between pruned and unpruned plantation E. nitens trees. Veneer recoveries of 58% and 45% were achieved for pruned and unpruned logs respectively although a wide variation between trees was noted. A wide variation was also reported for veneer properties such as density and stiffness MoE).

Similar studies involving veneer processing plantation eucalypt species have been completed outside Australia with similar experiences and results (e.g. Bortoletto 2003, McKenzie et al. 2003, Almeida et al. 2004, Jaeger and Ziger 2007, Guimaraes et al. 2008, Iwakiri et al. 2013).

As an alternative development approach and prompted by the availability of substantial areas of young, small-diameter hardwood plantation logs, mainly from the Eucalyptus, Populus and Acacia genus; China has led the advancement of spindleless lathes as a means to more efficiently process their available young fast growing plantation hardwood resources into solid products. Spindleless lathes are also referred to as ‘chuckless lathes’ or ‘centreless lathes’. Baldwin (1995) reports that in 1987 Durand Raute Industries Ltd first developed and manufactured a spindleless lathe, however
various design patents have existed since the 1930’s (e.g. United State Patent Office patent no. 1,951,834, dated March 20 1934).

The fundamental difference with this alternative veneer processing method rests with the billet rotary drive mechanism. While a spindled lathe relies on spindles located at the billet ends to position the billet in the lathe and to transfer the rotary drive, spindleless lathes have a series of power driven rollers positioned parallel to the knife which rotate against the billet periphery turning the billet against the knife (Figure 5). Similar to a spindled lathe, spindleless lathes also utilise a nose bar arrangement located near the knife, however the nose bar on a spindleless lathes are often a power driven roller design which further assists with the rotation of the billet.

![Figure 5. Spindleless veneer lathe.](image)

Without the reliance on spindles to hold the billet in position through a relatively concentrated zone, spindleless lathes are proving to be very successful in processing
logs with qualities below that previously accepted. Species more prone to end-splitting can be peeled with a reduced risk of the splits becoming worse during peeling. In fact, unlike spindles that force the splits further apart, the peripheral drive mechanisms on a spindleless lathe effectively presses the splits together during peeling. In addition, without spindles which limit the minimum peeled billet diameter and result in relatively large peeler cores, from which no veneer can be recovered, spindleless lathes are able to recover veneer from billets to a much smaller diameter. While spindleless lathes still produce peeler cores, their diameters are often in the order of 20 – 50 mm. Figure 6 provides illustration of a peeler core produced from a standard spindled rotary veneer lathe in operation in Australia and a peeler core produced from a spindleless veneer lathe.

Figure 6. A 45 mm peeler core on the left produced from a spindleless veneer lathe compared to a 130 mm peeler core produced from a standard commercial spindled lathe.

The resulting small peeler core size also means that billets with smaller starting diameters can also be more profitably peeled. For these reasons, spindleless lathes have
been adopted mostly in situations where a large supply of small diameter and sub-optimum quality billets exist (i.e. young, fast-grown hardwood plantations). Also, in contrast to the evolution of spindled lathe development, spindleless lathes have been developed based on lean manufacturing principles meaning the equipment design is comparatively simple and involves significantly lower capital cost by comparison.

Arnold et al. (2013) reported that there are more than 5,000 small-scale veneer mills in China dedicated to the processing of young, small-diameter eucalypt logs and the adoption of spindleless lathe technology dramatically changed China’s veneer processing industry because there was 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 could be processed economically to yield high value veneer (Luo et al. 2013). A key to China’s production success is the large number of small-scale operations located close to the forest resource: each one is using equipment with a low capital cost and dependent on the availability of low-cost labour.

Many Asian countries, in particular China, have a well-established industry based on processing hardwoods (including eucalypts) with a large number of operations using spindleless lathes. However, published literature detailing the process protocols and information of veneer quality and recovery from spindleless lathe methods are limited. Of the publications available, most are restricted to analyses comparing genetics or forest management systems within research plots and in-depth recovery, grade quality, defect and properties analysis is limited (e.g. Peng et al. 2014; Luo et al. 2013; Arnold et al. 2013) and therefore restricts the transfer of knowledge to other resources and in contexts like Australia. There are some experiences within South America in processing
young, fast grown eucalypt species, but again, much of the experience and developments exist as ‘grey literature’ and are unpublished.

Published scientific literature is limited on research that has been undertaken on trialling the performance of spindleless lathes for the processing of Australian grown plantation hardwoods. Zbonak et al. 2012 utilised a spindleless veneer lathe to process plantation grown C. citriodora and E. dunnii during a trial designed to determine the effects of thinning and pruning. While some veneer recovery and grade quality data was collected for the purpose of assessing the impacts of specific silvicultural regimes, the trial was not designed to analyse the processing aptitude of the spindleless technology for a wide range of tree characteristics and wood quality.

1.2  Research Aims and Objectives

Rotary veneer processing and the manufacture of veneer-based composite products are potential processes and product streams that may be able to more efficiently use Australian grown plantation hardwood logs. Compared to alternative processing methods, veneer processing is able to better accommodate the characteristics of young, fast-grown plantation hardwoods such as small diameters, growth stresses and large gradients of within tree properties. The processing method can potentially achieve high recoveries and better recovery of the outer part of the tree containing more attractive properties.

Many challenges remain with the direct adoption of traditional spindled lathe methods. Alternative veneer processing methods incorporating spindleless approaches which have
emerged in recent years are potentially better suited to this resource, giving the possibility for greater recovery and improved quality. While the spindleless lathe approach is not necessarily new, designs have improved significantly in recent years, both in terms of cost and engineering performances. The development of this method has focused on an efficient processing solution for very young plantations containing very small log diameters and low to mid density species. While the approach is reported to be widely adopted in some countries including China and Vietnam, limited information exists describing the performances and output quality of the newly developed, but still relatively simple engineering design. The application of this processing method for the conversion of Australian grown plantation hardwoods, which include very different species grown under very different growing conditions (i.e. climate and management), remains untested.

The species growing within Australian hardwood plantations have very different wood properties and log geometry than those targeted during the advancement of spindleless processing methods. Previous wood quality studies have confirmed that the wood properties of plantations differ from mature native forest sourced wood and the fast growing conditions in plantations enlarge the volume of wood in the juvenile stage. These studies have identified a large variation of wood properties within plantation trees and a significant radial increase in properties from the tree centre towards the periphery. Despite the completion of many studies, a lack of detailed understanding remains on the evolution of key properties as young trees grow and transition from juvenile to mature wood. Furthermore, the understanding of how the variations of many wood properties are recovered during processing remains unknown.
Existing literature acknowledges that defects such as knots and gum defects are present in much higher proportions in plantation-grown wood compared to wood sourced from native forest, however these previous studies haven’t been able to facilitate a comprehensive understanding of how these defects will present at the completion of veneer processing. In addition, the impact of common silvicultural treatments on defect size and frequency are not well understood. Pruning for example, is undertaken in order to minimise knots and encourage clear wood production. Silviculture treatments such as pruning induce significant investments during the plantation cycle with the goal of improving wood quality and therefore value. However, it remains unclear how defects are presented in veneer produced from Australian hardwood plantations, the effectiveness of silvicultural treatments to influence wood defects (both size and frequency) and whether a gain in value can be realised are still unknown variables in the value chain. This is especially true for veneer produced with spindleless processing methods as more of the tree volume is converted into veneer.

The lack of knowledge of how spindleless lathe processing methods are able to process logs from Australian hardwood plantations, a deficiency of understanding of the expected wood defects and the wood properties that result, prevent an evaluation of the end products performances and the suitability for commercial adoption.

As a consequence, the objective of this dissertation was to analyse small-log processing through the application of lean spindleless rotary veneer processing methods to achieve rotary veneer for structural purposes from Australian-grown, juvenile hardwood
plantations. More specifically, the study sought to answer the following research questions:

1. What results from the interaction between Australian-grown plantation grown hardwoods and spindleless veneer processing methods?
2. What is the frequency and severity of wood defects that result in rotary veneer produced from processing Australian plantation grown hardwoods using spindleless veneer processing methods?
3. How do key wood mechanical properties vary between plantation species and how are the variable wood properties recovered in rotary veneer produced when using spindleless veneer processing methods?
4. Are the recovered wood performances (wood defects and key wood properties) of rotary veneer suitable for the commercial use for structural purposes?

To provide an understanding of the application of spindleless lathes for the processing of plantation hardwoods, processing trials were designed that aimed to quantify log and grade recoveries from logs harvested from six commercially important Australian-grown plantation hardwood species (Figure 6). The species selection ranged from pulpwood to solid wood species sourced from temperate to tropical areas. 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). Trees were sampled so that they were representative of the average resource currently available for the industry’s use now and in the immediate future. Evaluation methods sought to be aligned with common industry methods and assessment criteria. Chapter 2 details the analysis of the log and veneer grade recoveries resulting from the
processing of 918 logs using spindleless veneer processing technology and best practice commercial processing methods.

Detailed wood defect assessments were conducted to provide an understanding of the defects that result in veneer produced from Australian hardwood plantations trees when processed using spindleless rotary veneering methods. The assessments aimed to quantify the wood defects present in veneers recovered from the processing trials (Chapter 2). Further analysis applying industry grading standards would allow grade recoveries to be determined in line with commercial practices. The adopted approach aimed to quantify the impact of individual wood defect types on grade recovery including the identification of defects that limit higher veneer grades from being achieved. Grade scenarios using the wood defect data collected aimed to model the effects of potential defect management strategies. Chapter 3 details the analysis at a species level, of wood defects that occurred in veneer which was produced during the processing trials.

Further analysis of wood defects that occurred in veneer recovered from different plantations of the same species aimed to describe the variation that occurs inside a species within the plantation estate. Furthermore, the selection of plantations that include different growing conditions and silvicultural treatments would facilitate comparison of veneer grade recoveries between sites and test the grade scenarios described above. The species included *E. globulus* and *E. nitens*. Three plantations for each of the two species were included in the evaluation. Chapter 4 reports the wood defect analysis including variation in grade recoveries that occurred from within a
species between plantation locations. The validity of grade scenarios developed in Chapter 3 was tested.

To better quantify the veneer suitability for structural veneer-based products, veneer stiffness, assessed through the modulus of elasticity (MoE), and density were assessed on the veneer recovered from the processing trials (Chapter 2). In particular, given that the veneering process essentially unrolls the billet with minimal waste, the gradient of MoE and density across the billet radius was described. The resulting properties variation and impact on the recovered veneer qualities is reported in Chapter 5.
Figure 6. Experimental plan

- Resource
- Pre-treatment
- Peeling
- Clipping

1. Resource
   - Six plantation hardwood species
   - Commercially important species for Australia
   - Representative of the available resource

2. Pre-treatment
   - Target 75°C billet core temperature
   - 100% RH/90°C for approximately 24 hours

3. Peeling
   - Spindleless veneer lathe
   - Nominal dried veneer thickness of 2.4 mm, 2.5 mm and 3.0 mm

4. Clipping
   - Veneer ribbon clipped for veneer sheets and sample strips
   - Veneer sheets 1,400 mm maximum width
   - 150 mm wide sample strips removed from between each veneer sheet
   - Veneer dried to 10% moisture content

5. Recovery Analysis
   - Green recovery
   - Gross recovery
   - Net recovery
   - Grade recovery
   - AS/NZS2269.0:2012 – industry accepted grading standard
   - A, B, C, D and reject grades
   - Species level analysis (bulked)

6. Grade Analysis
   - AS/NZS2269.0:2012 – industry accepted grading standard
   - A, B, C, D and reject grades
   - Defect analysis (resource related defects)
   - Species level analysis (bulked)
   - Grade scenarios modelled:
     - Optimisation of grading standard rules
     - Influence of silvicultural treatments

7. Forest Management Analysis
   - Plantation level analysis (2 species)
   - Forest management approaches compared (thinning and pruning)
   - Recovery analysis (green, gross and net recovery)
   - Grade analysis (AS/NZS2269.0:2012)
   - Defect analysis (resource related defects)
   - Silviculture modelled grade scenarios evaluated

8. Veneer Properties Analysis
   - Density, dynamic modulus of elasticity (MoE), and specific MoE.
   - Measured on sample strips
   - Mathematic modelling of properties to describe variation across the billet radius and along the recovered veneer ribbon.
   - Species level analysis (bulked)
1.3 Expected contribution to science and industry

The research aimed to provide a novel set of data and information on the production of structural grade veneers from Australian-grown plantation hardwood species from across the plantation resources which are available now and in the immediate future for the industry’s use. The study design intended to provide new information at a scale covering the resource diversity which could be processed within an industrial facility.

This research is expected to have significant value for the scientific communities, the hardwood plantation industry and veneer processing industry. The research sought to combine engineering and processing sciences with wood science in order to evaluate the combination of new processing methods and relatively new forest resources. The study is expected to contribute to the field of wood science through improved understanding of the wood properties, wood defects and end-product performances from Australian grown hardwood plantations. The innovative methodology designed to describe wood properties and wood defects will provide an alternative to traditional study approaches.

Industry will gain a more accurate understanding of the plantation hardwood forest resource value through processing using new methods. Knowledge will be gained on the production of structural grade veneers from Australian-grown plantation hardwood species from the plantation resources which are available now and in the immediate future for the industry’s use. The study will identify the potential for industry to use the processing methods to produce veneer with properties suitable for marketable structural veneer-based products. Knowledge on the veneer grade and veneer mechanical properties recovered through processing trials will assist in the identification of
structural product end-uses that can make best use of the qualities produced from the plantation trees. With this knowledge, product development programs and marketing strategies can be analysed.

The connection between science and industry is further enhanced through the research being conducted at an industry facility scale. The assessment methodology adopted throughout the study remained directly connected to industry adopted systems. Recovery analyses enable technical and economic comparisons to existing and more traditional processing methods and forest resources. Grade evaluations were performed using industry accepted grading systems and mechanical properties assessments were directly linked to the systems and data requirements that are used by industry for the manufacture of veneer-based engineered wood products.
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of thinning and conventional processing practices on sawn board quality and recovery,”


CHAPTER 2: Veneer recovery analysis of plantation eucalypt species using spindleless lathe technology

Veneer Recovery Analysis of Plantation Eucalypt Species Using Spindleless Lathe Technology

Robert L. McGavin, a,b,*, Henri Bailleres, b Fred Lane, b David Blackburn, c Mario Vega, c and Barbara Ozarska a

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

Contact information: a: University of Melbourne, Department of Forest Ecosystem Science, 500 Yarra Boulevard Richmond, Victoria 3121 Australia; b: Queensland Department of Agriculture, Fisheries and Forestry, Horticulture and Forestry Science, Salisbury Research Facility, 50 Evans Road, Salisbury, Queensland 4107 Australia; c: School of Plant Science and National Centre for Future Forest Industries, University of Tasmania, Private Bag 55, Hobart, Tasmania 7001 Australia;
*Corresponding author: robbie.mcgavin@daff.qld.gov.au

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 (Gavan 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; 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 fast-
grown 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

<table>
<thead>
<tr>
<th>Species</th>
<th>Main Traditional Market</th>
<th>Age (years)</th>
<th>Plantation Location</th>
<th>Number of Trees</th>
<th>Average DBHOB * (cm)</th>
<th>Number of Billets</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Corymbia citriodora</em> subsp. <em>variegata</em></td>
<td>Sawn timber</td>
<td>10–12</td>
<td>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).</td>
<td>80</td>
<td>20.6 (2.5)</td>
<td>215</td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
<td>Sawn timber</td>
<td>12–15</td>
<td>Pomona, Queensland (26°23'S, 152°52'E); and Beerburrum, Queensland (26°23'S, 152°52'E).</td>
<td>55</td>
<td>31.9 (6.3)</td>
<td>223</td>
</tr>
<tr>
<td><em>Eucalyptus dunnii</em></td>
<td>Pulp and fibre</td>
<td>11</td>
<td>Urbenville, New South Wales (28°28'S, 152°35'E).</td>
<td>60</td>
<td>22.9 (3.5)</td>
<td>148</td>
</tr>
<tr>
<td><em>Eucalyptus pellita</em></td>
<td>Sawn timber</td>
<td>13</td>
<td>Ingham, Queensland (18°40'S, 146°8'E).</td>
<td>38</td>
<td>28.1 (4.3)</td>
<td>130</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Pulp and fibre</td>
<td>20–22</td>
<td>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).</td>
<td>41</td>
<td>34.0 (7.4)</td>
<td>82</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Pulp and fibre</td>
<td>13–16</td>
<td>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).</td>
<td>60</td>
<td>30.6 (3.7)</td>
<td>120</td>
</tr>
</tbody>
</table>

* 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,

\[ V = \left( \frac{SEDUB + LEDUB}{2} \right)^2 \times \frac{\pi}{4} \times L \]  

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

\[ D_{CALC1} = SEDUB - S \]  

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.

\[ D_{CALC2} = SD - S \]  

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 \textit{Eucalyptus dunnii} and \textit{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 \textit{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 practices (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 \((\pm 0.01 \text{ mm})\) 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 \((GNR \text{ as } \%)\) was calculated as follows,

\[
GNR = \left( \frac{L \times \sum_{\text{vener}} (GT_{\text{vener}} \times GW)}{\sum_{\text{billet}} V} \right) \times 100
\]  

\( (4) \)

where \( GT_{\text{mean}} \) 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,

\[
GSR = \frac{L \times \sum_{\text{veneer}} (DT_{\text{mean}} \times GRW)}{\sum_{\text{billet}} V} \times 100
\]

where \( DT_{\text{mean}} \) 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:

\[
NR = GSR \times 0.96 \times \frac{1200}{1300}
\]

thus \( NR = GSR \times 0.88615 \)

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

<table>
<thead>
<tr>
<th>Species</th>
<th>Average Billet Small-end Diameter Under Bark (cm)</th>
<th>Average Billet Volume (m$^3$)</th>
<th>Total Volume Processed (m$^3$)</th>
<th>Average Sweep * (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corymbia citrioidra subsp. variegata</td>
<td>15.6 (2.52)</td>
<td>0.028 (0.009)</td>
<td>5.936</td>
<td>11 (5.09)</td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td>23.5 (5.23)</td>
<td>0.082 (0.027)</td>
<td>13.884</td>
<td>12 (6.98)</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>17.5 (3.31)</td>
<td>0.035 (0.014)</td>
<td>5.165</td>
<td>10 (5.20)</td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
<td>20.9 (3.84)</td>
<td>0.049 (0.019)</td>
<td>6.354</td>
<td>11 (4.77)</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td>28.9 (7.09)</td>
<td>0.095 (0.052)</td>
<td>7.778</td>
<td>8 (4.33)</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>25.7 (3.47)</td>
<td>0.072 (0.020)</td>
<td>8.659</td>
<td>11 (5.22)</td>
</tr>
</tbody>
</table>

* 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 citrioidra 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

<table>
<thead>
<tr>
<th>Species</th>
<th>N</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus nitens</td>
<td>70</td>
<td>7.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>146</td>
<td></td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
<td>129</td>
<td></td>
<td>10.9</td>
<td>10.9</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>120</td>
<td></td>
<td>11.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Corymbia citriodora subsp variegata</td>
<td>213</td>
<td></td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td>141</td>
<td></td>
<td></td>
<td>12.2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Species</th>
<th>Calculation Method 1 ($r^2$)</th>
<th>Calculation Method 2 ($r^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corymbia citriodora subsp variegata</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>0.86</td>
<td>0.90</td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>0.87</td>
<td>0.91</td>
</tr>
</tbody>
</table>

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*, *Eucalyptuspellita*, and *Eucalyptus cloeziana* each achieved recoveries within a close range (75% to 73%). *Eucalyptus dumii* had a recovery (70%) between this group and *Corymbia citriodora* subsp. *variegata*.

**Table 5. Veneer Recoveries**

<table>
<thead>
<tr>
<th>Species</th>
<th>Green Recovery (GNR as %)</th>
<th>Gross Recovery (GSR as %)</th>
<th>Gross Recovery Percentage of Green Recovery (%)</th>
<th>Net Recovery (NR as %)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Corymbia citriodora</em> subsp. <em>variegata</em></td>
<td>68</td>
<td>54</td>
<td>81</td>
<td>48</td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
<td>73</td>
<td>65</td>
<td>88</td>
<td>58</td>
</tr>
<tr>
<td><em>Eucalyptus dumii</em></td>
<td>70</td>
<td>62</td>
<td>89</td>
<td>55</td>
</tr>
<tr>
<td><em>Eucalyptuspellita</em></td>
<td>74</td>
<td>62</td>
<td>83</td>
<td>55</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>75</td>
<td>62</td>
<td>84</td>
<td>55</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>77</td>
<td>57</td>
<td>75</td>
<td>50</td>
</tr>
</tbody>
</table>

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 dumii*, *Eucalyptuspellita*, 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 dumii* aged between 12 and 34 years. Similar recovery values are reported by Blakemore et al. (2010) for a small veningering 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

<table>
<thead>
<tr>
<th>Species</th>
<th>N</th>
<th>Subset (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>120</td>
<td>75.2</td>
</tr>
<tr>
<td><em>Corymbia citriodora</em></td>
<td>215</td>
<td>80.7</td>
</tr>
<tr>
<td><em>Eucalyptus pellita</em></td>
<td>130</td>
<td>82.8</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>82</td>
<td>83.5</td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
<td>219</td>
<td>88.0</td>
</tr>
<tr>
<td><em>Eucalyptus dunnii</em></td>
<td>166</td>
<td>88.8</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Table 7. Graded Veneer Recoveries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
</tr>
<tr>
<td>0.2 (0.3)</td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
</tr>
<tr>
<td><em>Eucalyptus dunnii</em></td>
</tr>
<tr>
<td><em>Eucalyptus pellita</em></td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
</tr>
</tbody>
</table>

* 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).

ACKNOWLEDGMENTS

The authors are grateful for the support of the Queensland Government, Department of Agriculture, Fisheries and Forestry, Cooperative Research Centre for Forestry, the National Centre of Future Forest Industries, the Forest and Wood Products Australia, and the Engineered Wood Products Association of Australasia. The following companies and individuals also are acknowledged for providing the plantation resource, assistance with labour and equipment, and access to the trial sites: HQ Plantations Pty Ltd, Forestry Tasmania, Australian Bluegum Plantations of Victoria, New Forests of Victoria, PF Olsen of Victoria, and private plantation grower David Swann, Victoria. Austral Plywoods also are acknowledged for technical support and access to commercial facilities for veneer seasoning.

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CHAPTER 3: Veneer grade analysis of early to mid-rotation plantation *Eucalyptus* species in Australia

Veneer Grade Analysis of Early to Mid-rotation Plantation *Eucalyptus* Species in Australia

Robert L. McGavin, b, c, * Henri Bailleres, b Fred Lane, b Joh Fehrmann, b and Barbara Oszarska a

Processing Australian hardwood plantations into rotary veneer can produce more acceptable marketable product recoveries compared to traditional processing techniques (e.g. sawmilling). Veneers resulting from processing trials from six commercially important Australian hardwood species were dominated by D-grade veneer. Defects such as encased knots, gum pockets, gum veins, surface roughness, splits, bark pockets, and decay impacted the final assigned grade. Four grading scenarios were adopted. The first included a change to the grade limitations for gum pockets and gum veins, while the second investigated the potential impact of effective pruning on grade recovery. Although both scenarios individually had a positive impact on achieving higher face grade veneer qualities, the third and fourth scenarios, which combined both, had a substantial impact, with relative veneer values increasing up to 18.2% using conservative calculations (scenario three) or up to 22.6% (scenario four) where some of the upgraded veneers were further upgraded to A-grade, which attracts superior value. The total change in veneer value was found to depend on the average billet diameter unless defects other than those relating to the scenarios (gum or knots) restricted the benefit of pruning and gum upgrading. This was the case for species prone to high levels of growth stress and related defects.

*Keywords: Eucalyptus; Veneer; Plantation; Grade quality; Value; Pruning; Recovery*

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

**INTRODUCTION**

The commercial forest resource in Australia is undergoing considerable change with a greater proportion of plantation grown forest becoming available to the wood processing sector. While the industry’s softwood sector in Australia has become well established over recent decades with reliance on a plantation resource, the hardwood sector remains largely dependent on native forests for log supply. It is therefore this sector that can expect the greatest change in the available forest quality and quantity with the continuing transition from native forest towards plantation grown forests.

Gavran (2013) reports that over two million hectares of plantation forestry exist in Australia, of which about one million hectares are hardwood species. Of this one million hectare hardwood estate, around 84% have been established for pulpwood production (Gavran 2013). While some small areas of plantations have been established and managed with a high-value product focus, 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.
Despite the original plantation establishment and management intent, less than favourable market conditions for Australian pulpwod have prompted the exploration of alternative higher value markets. As summarised by McGavin et al. (2014), many studies have been completed that investigated solid wood processing options (i.e., sawmilling) for the plantation hardwood resource. 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 hardwood from plantations into veneer using relatively new small-scale spindleless veneer lathe technology has the potential to produce product recoveries that are much more favourable when compared to solid wood processing techniques (McGavin et al. 2014). While the technology approach is not necessarily new, recent advancements in design allow the technology to be well suited to smaller 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) report well over 5000 small-scale veneer mills operating in China.

While the veneer recoveries reported by McGavin et al. (2014) were high (net recoveries up to 58% of log volume), the grade recoveries were dominated by D-grade veneers when graded to Australian and New Zealand Standard AS/NZS 2269.0:2012 (Standards Australia 2012). The low recovery (between 3% and 32% of total veneer) of higher grade veneers (C-grade and better) has been identified by McGavin et al. (2014) as a challenge for commercial panel production with insufficient proportions of face veneer qualities to allow a standard commercial mix of structural panel products to be manufactured when only using a resource of this quality.

The objective of this study was to analyse at a species level, the grade quality, including defect assessment of veneer which resulted from the processing studies reported by McGavin et al. (2014). In addition, defects that had the most influence in reducing grade quality are reviewed and scenarios explored to determine the improvements in grade recovery and relative value that may be possible under different circumstances. The resulting analysis will provide guidance on the quality of the current plantation resources, on plantation management programs and product development, and marketing strategies.

EXPERIMENTAL

Materials

Veneer processing

Veneers were sourced from processing studies conducted on billets harvested from Australian commercial plantation stands representing the average resource currently available for industry to access now and in the immediate future (McGavin et al. 2014). Six (6) of the major commercially important Australian hardwood species were included and ranged from traditional pulp to high quality solid wood species. They include Corymbia citrodora 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). Plantation ages ranged between 10 and 16 years for all species except Eucalyptus nitens, which was between 20- and 21-years-old.
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 peeler core size was 45 mm. For the very small number of *E. nitens* billets that were too large (> 400 mm diameter) 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 spindleless lathe. For this study, the nominal dried veneer thicknesses were 2.4, 2.5, or 3.0 mm, depending on species 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. Veneer widths down to 300 mm were included while veneer sheets narrower than 300 mm were discarded, with the exception of a number of 150 mm wide sheets specifically targeted for veneer property evaluations (details not reported). Although 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. Clipped veneer was seasoned through a conventional jet box veneer drying system according to standard commercial practices in Australia (temperatures ranged from 160 to 190 °C during drying) with a target moisture content of 5%. Veneers were then stabilised to 10% moisture content in storage.

More detailed description of the methodology regarding plantation selection, billet preparations, and processing is described by McGavin et al. (2014).

**Methods**

**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 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.

Apart from a slight variation in veneer thickness, the lathe settings and log conditioning were fixed for all species. Moreover, to facilitate comparisons between species, only resource-related defects have been included in this analysis. Defects that could be directly attributed to the veneering process, such as splitting caused by veneer handling, have been excluded from the analysis so as to not disadvantage any particular species that may benefit from a further refined process. For each veneer, the visual grade was recorded for each type of defect present within the veneer. This allowed the analysis of the impact of each defect type in terms of its contribution to the assigned grade of each veneer. The defect(s) causing the lowest visual grade was identified as the grade limiting defect(s) and the resulting assigned grade was recorded for each veneer. 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.

**Grade scenarios**

Four realistic scenarios were adopted to explore the opportunity of improving the volume recovered of higher grade qualities (i.e., higher value veneers) and included:

1. the reduction of grade impact from gum (or kino) pockets and gum veins;
2. the reduction of knots (sound and encased knots) as well as defects known to be associated with knots (e.g., roughness, decay and bark) through effective pruning;
3. the combination of gum defect upgrade and effective pruning (i.e., scenarios one and two combined); and
4. the combination of gum defect upgrade and effective pruning (i.e., similar to scenario three) with additional upgrading to higher veneer grades.

The first scenario focused on gum pockets and gum veins. These defects are cavities in the wood containing a natural dark-coloured phenolic exudation (Standards Australia 1997). Although commonly referred to as gum, Hillis and Brown (1984) note the more accurate name of kino when referencing its presence in *Eucalyptus* species. They note the extent of the presence varies according to species, bark thickness, tree vigour, and other environmental and genetic factors and is one of the most frequently mentioned causes of degradation in eucalypt timber. The presence of gum in either pockets or veins is usually a defensive response from the tree against injury, which may occur from insect damage, mechanical damage, or fire (Bootle 2010).

The Australian and New Zealand standard AS/NSZ 2269.0:2012 (Standards Australia 2012) excludes the presence of any gum pockets or gum veins from A-grade and B-grade, excludes gum pockets but permits gum veins in C-grade, and permits both gum pockets and gum veins in D-grade. During the grading, it became obvious that a significant quantity of veneer sheets were being downgraded to C-grade and often D-grade due to very minor occurrences of either gum veins and/or gum pockets within a veneer sheet. Given the minimal visual and mechanical impact that these defects have, especially given the small size and low concentration which potentially have less aesthetic impact compared to other reasonably permitted defects, it was hypothesised that the grading standard had probably been developed with a focus on other forest resources where these defects are less frequently occurring (e.g., plantation softwood and mature native forest hardwood) which potentially unnecessarily disadvantages plantation hardwood veneer.

On this basis, the first grading scenario assumed that the grade limitations relating to gum pockets and gum veins will be reduced, resulting in D-grade and C-grade veneers being able to achieve C-grade and B-grade, respectively, when graded against these defects.

The second scenario focused on the reduction of knots (sound and encased knots) as well as other defects known to be associated with knots including veneer roughness, decay, and bark. This scenario was included in order to explore the possible grade improvements that can be achieved if effective pruning is conducted early in the rotation, resulting in a greater portion of the veneer being free from these defects after knot occlusion is achieved. The roughness upgrade of the veneer was included in this scenario with the knowledge that unacceptable roughness occurred mostly around knots and the zone of knot occlusion where grain deviation was present. A statistical analysis of the correlation between roughness and knots further supported the inclusion of roughness in the scenario.

Several studies and reviews on pruning commercial *Eucalyptus* species indicate that, on average, the pruning diameter under bark of a stand for the first 6 m log is around 8 cm (Dickinson et al. 2000; Nolan et al. 2005; Wood et al. 2009; Forrester et al. 2010; Alcorn et al. 2013). This average pruning diameter confirms the
information provided by most Australian growers about the implemented silvicultural practices. The other critical information necessary to assess the impact of pruning on veneer grading is the branch occlusion thickness before the tree produces wood free of knots and knot-related defects. According to the studies performed by Montagu et al. (2003), Pinkard et al. (2004), Smith et al. (2006), O’Hara (2007), Liu et al. (2012), and Forrester et al. (2013), the occlusion thickness can be estimated depending on the type of species. For the fast-growing pulp species in this study (E. dunnii and E. globulus), the occlusion thickness is on average 2 cm. For the other species, the occlusion thickness is on average 3 cm.

The average pruning diameter (8 cm), the occlusion thicknesses (2 cm or 3 cm), and the average billet diameter for each plantation stand were used to develop the pruning scenarios for each species. For each species, the average diameter was calculated for each plantation stand from the billet diameters. The average pruning diameter plus two times the occlusion thickness of the species (either 4 cm or 6 cm) was divided by the average billet diameter of the plantation stand to calculate the average diameter ratio from which a pruned billet would start to produce wood free of knots and related defects. This ratio was then applied to each billet of the plantation stand in order to establish the diameter at occlusion. This approach acknowledges the range of billet diameters at time of harvesting and ensures the calculated occlusion diameters were proportional to the size of the billet at the time of pruning. This means the bigger trees at time of harvesting have a larger diameter at pruning and conversely smaller trees have a smaller diameter at pruning. The pruning scenario implies that the veneer grade is not altered for veneer which was recovered from within the occlusion diameter. This scenario assumes that veneer produced from the remaining outer section of the billets contained no sound knots, encased knots, bark and decay, holes, and defect combination, and, had satisfactory veneer roughness resulting in veneers being upgraded to B-grade (unless veneers already attained A-grade). For these defects, it can be reasonably assumed that some veneers in the outer part of the billet may produce A-grade veneers. Unfortunately, it was not possible to assess with enough confidence this proportion, so consequently the B-grade upgrading strategy was considered reasonable for this scenario, despite being slightly conservative.

Scenario three combined the effects of gum defect upgrade (scenario one) and effective pruning (scenario two). Scenario four also combined the effects of scenarios one and two but with a less conservative grade upgrading strategy allowing 25% of B-grade veneers resulting from the scenario being further upgraded to A-grade.

Accurate commercial veneer values for the species included in the study were difficult to determine; however, to provide an indication of the potential economic impact that the four grade scenarios may have on veneer value, comparable values for each visual grade were provided by Engineered Wood Products Association of Australasia (2014). This suggests that C-grade veneer attracts a value 1.2 times higher than D-grade, B-grade attracts a value 1.7 times than D-grade, and A-grade attracts a value 3 times higher than D-grade.

Statistical analysis

A Spearman’s rank-order correlation was run on ordinal variables (veneer grades) to assess the relationship between veneer roughness and knots (sound and encased) using IBM SPSS version 22.0 (IBM SPSS Statistics for Windows, IBM Corp., Armonk, NY, USA). The ordinal variables represent paired observations and a monotonic relationship between variables exists as assessed by visual inspection of scatterplots. The confidence interval level was 95%.

RESULTS AND DISCUSSION

Visual Grading
A total of 918 billets (48 m³) from six different hardwood species were processed using a spindleless lathe which produced 8539 m² of rotary veneer. Table 1 provides details of the total surface area of veneer recovered and the grade recovery (recovered grade veneer as a proportion of veneer surface area) for each species.

Table 1. Graded Veneer Recovery

<table>
<thead>
<tr>
<th>Species</th>
<th>Total surface area of veneer graded (m²)</th>
<th>A-grade recovery (%)</th>
<th>B-grade recovery (%)</th>
<th>C-grade recovery (%)</th>
<th>D-grade recovery (%)</th>
<th>Reject recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corymbia citriodora subsp. variegata</td>
<td>796</td>
<td>0.5</td>
<td>1.8</td>
<td>17.9</td>
<td>73.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td>2619</td>
<td>0.3</td>
<td>6.1</td>
<td>28.8</td>
<td>60.1</td>
<td>4.7</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>938</td>
<td>0.0</td>
<td>0.5</td>
<td>16.0</td>
<td>79.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Eucalyptus poliata</td>
<td>1089</td>
<td>0.1</td>
<td>4.6</td>
<td>10.6</td>
<td>80.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td>1442</td>
<td>0.4</td>
<td>11.1</td>
<td>15.2</td>
<td>67.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>1655</td>
<td>0</td>
<td>1.1</td>
<td>2.7</td>
<td>84.3</td>
<td>11.9</td>
</tr>
</tbody>
</table>

Figures 1 to 5 provides an example of the visual quality demanded by each grade, with A-grade veneer being the highest quality followed by B-grade, C-grade and D-grade. F-grade (or reject) veneers fail to meet the grade requirements of the Australian and New Zealand standard AS/NSZ 2269.0:2012 (Standards Australia 2012).

Fig. 1. Example of the visual quality of A-grade veneer

Figures 6 to 11 illustrate the distribution of assigned grades for individual grade limiting defects for each species. In this type of diagram, each bubble represents the percentage of a given grade for a given defect. The grey scaling and diameter of the bubble both are proportional to the percentage of the total veneer surface area for each individual defect. In addition, similarly for each defect, the assigned grade is determined for each veneer from the defect(s) causing the lowest visual grade.

The graded recovery is dominated by D-grade veneer across all species. This is consistent with other similar studies such as Peng et al. (2014) who reported over 80% of eucalypt hybrid veneers being categorised as D-grade (although based on a slightly different grading standard) and less than 3% of veneers meeting the grade requirements of C-grade or better (with the balance being reject grade). The low recovery of higher grade veneers (C-grade and better) will make the commercial production of a standard mix of saleable structural panel products challenging due to insufficient proportions of more market acceptable quality veneers, mostly to be used as faces on panels. The Engineered Wood Products Association of Australasia (2015) suggest the rotary veneer industry requires approximately 30% to 40% of their graded
veneer production to be at least C-grade or better to enable saleable product manufacture. *Eucalyptus cloeziana* is the only species to be within this specified range (35%). All other species failed to achieve greater than 30% C-grade or better veneers. Blakemore et al. (2010) reports much more favourable grade recoveries for a small study which processed 10 *E. nitens* trees as part of a silviculture research trial.

![Diagram](image1)

**Fig. 6.** Distribution of *Corymbia citriodora* subsp. *variegata* visually assigned veneer grades for a range of resource related defects. Like the grey scale, the size of the circle is proportional to the recovered value.

![Diagram](image2)

**Fig. 7.** Distribution of *Eucalyptus cloeziana* visually assigned veneer grades for a range of resource related defects. Like the grey scale, the size of the circle is proportional to the recovered value.

A relevant comparison between studies is difficult due to differing sampling scale, processing technology adopted (i.e., spindles versus spindleless lathes), tree size, and grading standards adopted.

Fig. 8. Distribution of *Eucalyptus dunnii* visually assigned veneer grades for a range of resource related defects. Like the grey scale, the size of the circle is proportional to the recovered value.

Fig. 9. Distribution of *Eucalyptus pellita* visually assigned veneer grades for a range of resource related defects. Like the grey scale, the size of the circle is proportional to the recovered value.

Fig. 10. Distribution of *Eucalyptus nitens* visually assigned veneer grades for a range of resource related defects. Like the grey scale, the size of the circle is proportional to the recovered value.

Fig. 11. Distribution of *Eucalyptus globulus* visually assigned veneer grades for a range of resource related defects. Like the grey scale, the size of the circle is proportional to the recovered value.

Table 2 illustrates the five highest ranked defects (in order of severity) which prevented veneers from attaining assigned grades higher than D-grade for each species.

Table 2. Top Five Ranked Defects Preventing Veneers from Attaining Assigned Grades Higher than D-grade

<table>
<thead>
<tr>
<th>Species</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corymbia citriodora</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>subsp. variegata</td>
<td>Gum pockets (63%)</td>
<td>Roughness (29%)</td>
<td>Encased knots (17%)</td>
<td>Splits (6%)</td>
<td>Holes (4%)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Eucalyptus cloeziana</strong></td>
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</tr>
<tr>
<td></td>
<td>Gum pockets (40%)</td>
<td>Roughness (17%)</td>
<td>Bark or decay (16%)</td>
<td>Encased knots (13%)</td>
<td>Splits (12%)</td>
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<td></td>
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<tr>
<td><strong>Eucalyptus dunnii</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Gum pockets (65%)</td>
<td>Roughness (34%)</td>
<td>Splits (28%)</td>
<td>Compression (7%)</td>
<td>Holes (4%)</td>
</tr>
<tr>
<td></td>
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<td></td>
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<tr>
<td><strong>Eucalyptus pellita</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gum pockets (70%)</td>
<td>Encased knots (68%)</td>
<td>Roughness (17%)</td>
<td>Splits (9%)</td>
<td>Holes (2%)</td>
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<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Eucalyptus nitens</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Encased knots (44%)</td>
<td>Bark or decay (41%)</td>
<td>Splits (19%)</td>
<td>Roughness (12%)</td>
<td>Defect combination (6%)</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Eucalyptus globulus</strong></td>
<td>Bark or decay (86%)</td>
<td>Gum pockets (62%)</td>
<td>Encased knots (60%)</td>
<td>Roughness (36%)</td>
<td>Compression (29%)</td>
</tr>
</tbody>
</table>

Note: The proportion of veneer impacted by each defect is provided in parenthesis.

For all species, with the exception of *E. nitens* and *E. globulus*, gum pockets had the most influence in restricting veneers from attaining assigned grades higher than D-grade. *Eucalyptus pellita* was the most affected, with 70% of veneer being downgraded to D-grade due to gum pockets, followed by *E. dunnii* (65%), *C. citriodora* subsp. variegata (63%), and *E. cloeziana* (40%). For *E. globulus*, gum pockets were ranked second for limiting grade with 62% of veneers being restricted to D-grade due to gum pockets. Gum pockets had minimal impact on the grade recovery of *E. nitens* (ranked 6), with only 5% of veneer being restricted to D-grade for this defect. While this defect was common across all species, with the exception of *E. nitens*, the size of this defect was often small and not concentrated. While it does influence the appearance qualities of the veneer, it will be expected to have negligible effect on mechanical properties or on the panel manufacturing process. The characteristics of this defect in the veneer across all species are such that it may be unnecessarily severe to downgrade such quantities of veneer to D-grade, especially when compared to other appearance affecting defects which are permissible in higher grades. A market acceptance analysis and review of the permissible limits outlined in the grading standards for this defect would be beneficial.

For *E. globulus*, the presence of bark pockets or decay, mostly surrounding knots, was the highest ranked grade limiting defect preventing 86% of veneer from attaining assigned grades higher than D-grade. It was second ranked grade limiting defect for *E. nitens* with 41% of veneer being downgraded to D-grade. Apart from a small amount of *E. cloeziana* veneer (16% downgraded to D-grade), the veneer grade ranks were not negatively impacted by these defects in the other species.

Encased knots had the most influence on *E. nitens* veneer, limiting 44% of veneer to D-grade. The presence of encased knots also resulted in 68% of *E. pellita* veneer and 60% of *E. globulus* veneer from attaining assigned grades higher than D-grade. *Corymbia citriodora* subsp. variegata, *E. cloeziana*, and *E. dunnii* were also impacted by encased knots; however, the smaller dimension of the defect in these species resulted in only 17%, 13%, and 1% of veneer, respectively, being limited to D-grade. For these species, the small dimensioned encased knots had more impact on
preventing veneers from achieving assigned grades higher than C-grade (66%, 35%, and 83% veneers, respectively, limited to C-grade).

Veneer surface roughness resulted in 36% of *E. globulus*, 34% of *E. dunnii*, 29% of *C. citriodora* subsp. *variegata*, 17% of *E. cloeziana*, 17% of *E. pellita*, and 12% of *E. nitens* veneer being prevented from attaining assigned grades higher than D-grade. Veneer surface roughness is mostly present in areas of veneer where there is grain deviation present, such as around knots and knots holes.

Veneer splits resulted in 28% of *E. dunnii*, 19% of *E. nitens*, 12% of *E. globulus*, 12% of *E. cloeziana*, 9% of *E. pellita*, and 6% of *C. citriodora* subsp. *variegata* veneer being prevented from attaining assigned grades higher than D-grade. For this assessment, only splits believed to be resource related (e.g., splits that originated from billet end checks) were included in the analysis, excluding splits that may have occurred during processing (e.g., veneer handling).

Unacceptable levels of compression resulted in 29% of *E. globulus* veneer being restricted to D-grade. The presence of this defect was obvious in dried veneer, with many veneers being ‘ripped’ and uneven. The presence of this defect can be attributed to the differential transverse shrinkage induced by the highly frequent presence of veins or casts of tension wood within this species (Washusen and Illic 2001). It has been described to cause product recovery losses in sawn timber (Washusen 2011). Low levels of compression were noted in other species and resulted in 7% of *E. dunnii*, 6% of *E. nitens*, 2% of *E. cloeziana*, 1% of *C. citriodora* subsp. *variegata*, and 1% of *E. pellita* veneers being restricted to D-grade.

Multiple defects that individually were within permissible limits of higher grades, but when combined in close proximity (i.e., defect combination), led to 14% of *E. globulus* and 6% of *E. nitens* veneers being prevented from attaining a grade higher than D-grade. In addition, 11% of *E. globulus* veneers, 5% of *E. pellita* and *E. nitens* veneers, 4% of *E. cloeziana* and *E. dunnii* veneers, and 1% of *C. citriodora* subsp. *variegata* veneers failed to make grade (i.e., reject) when defects are considered in combination.

*Eucalyptus globulus* and *E. nitens* veneers were the most affected by sound knots, but unexpectedly, with only 4% of veneer being limited to D-grade. All other species each had negligible quantities of veneer downgraded (< 1%) to D-grade due to sound knots. This result is the consequence of the relatively small diameters of the knots that were present in the veneers across all species. Sound knots did contribute to a spread across the higher grade qualities as a result of increasing limitations of defect size as the grade improved.

Similar to sound knots, a range of other defects (e.g., discoloration and insect tracks) were present, but these had minimal impact on limiting veneer grade qualities to D-grade; however, they did impact on the distribution of veneers amongst the higher grades.

**Correlation between Roughness Grade and Knot Grade**

A Spearman’s rank-order correlation was run to assess the relationship between veneer surface roughness rank and sound or encased knot rank. In most cases, there was a significant (p<0.001) and relatively weak positive correlation between sound or encased knot rank and veneer surface roughness rank, with the Spearman correlation coefficient ranging from 0.1 to 0.304 (Table 3). There was no correlation between sound knot rank and veneer roughness for *C. citriodora* subsp. *variegata* due to the low proportion of sound knots combined with a lower number of veneers on this species. Aside from the latter case, an increase in sound or encased knot grade rank was associated systematically with an increase in surface roughness.
grade rank. This correlation supported the addition of veneer roughness in the parameters involved in the pruning scenario.

**Table 3.** Spearman’s Rank-Order Correlation between Roughness and Knots Rank

<table>
<thead>
<tr>
<th>Species</th>
<th>Statistical parameters</th>
<th>Sound knot rank</th>
<th>Encased knot rank</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Correlation Coefficient 0.206** 0.100**</td>
<td>1127</td>
<td>1127</td>
</tr>
<tr>
<td></td>
<td>Significance (2-tailed) &lt;0.0001 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N 1219</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Correlation Coefficient 0.200** 0.168**</td>
<td>1219</td>
<td>1219</td>
</tr>
<tr>
<td></td>
<td>Significance (2-tailed) &lt;0.0001 &lt;0.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N 1937</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
<td>Correlation Coefficient 0.101** 0.279**</td>
<td>1937</td>
<td>1937</td>
</tr>
<tr>
<td></td>
<td>Significance (2-tailed) &lt;0.0001 &lt;0.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N 423</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Corymbia citriodora subsp. variegata</em></td>
<td>Correlation Coefficient 0.066 0.138**</td>
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<td>423</td>
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<tr>
<td></td>
<td>Significance (2-tailed) 0.173 0.004</td>
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<td></td>
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<tr>
<td></td>
<td>N 840</td>
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<td></td>
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<tr>
<td><em>Eucalyptus pollita</em></td>
<td>Correlation Coefficient 0.304** 0.228**</td>
<td>840</td>
<td>840</td>
</tr>
<tr>
<td></td>
<td>Significance (2-tailed) &lt;0.0001 &lt;0.0001</td>
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<tr>
<td></td>
<td>N 440</td>
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<td></td>
</tr>
<tr>
<td><em>Eucalyptus dunnii</em></td>
<td>Correlation Coefficient 0.200** 0.298**</td>
<td></td>
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<tr>
<td></td>
<td>Significance (2-tailed) &lt;0.0001 &lt;0.0001</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>N 440</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed)**

**Grade Scenarios**

Table 4 illustrates the impact on grade recovery as a result of a shift of permissible limits between grades relevant to gum pockets and gum veins. This grading scenario assumes that the grade limitations relating to gum pockets and gum veins are reduced, resulting in veneers D-grade and C-grade being able to achieve C-grade and B-grade, respectively, when graded against these defects (scenario one).

**Table 4.** Graded Veneer Recovery Percentage Assuming a Relaxation in the Grading Standard for Gum Veins and Gum Pockets

<table>
<thead>
<tr>
<th>Species</th>
<th>Grade recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-grade</td>
</tr>
<tr>
<td><em>Corymbia citriodora subsp. variegata</em></td>
<td>0.5% (0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
<td>0.3% (0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus dunnii</em></td>
<td>0.0% (0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus pollita</em></td>
<td>0.1% (0.1)</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>0.4% (0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>0.0% (0.0)</td>
</tr>
</tbody>
</table>

Note: The change in graded veneer recovery is provided in parenthesis.
The results show a substantial impact, with the sub-tropical and tropical species being the main beneficiaries. Applying this scenario, 52% of *E. cloeziana*, 45% of *C. citriodora* subsp. *variegata*, and 41% of *E. dunnii* achieved assigned grades of C-grade or better and therefore met and exceeded the target grade quality proportions nominated by the Engineered Wood Products Association of Australasia (2013) as necessary for commercial production of structural panel products (30% to 40%). The remaining species still failed to produce sufficient proportions of C-grade or better veneer (27% of *E. nitens*, 25% of *E. pellita*, and 5% of *E. globulus* veneers).

Table 5 illustrates the impact on grade recovery that can be possible if effective pruning can be conducted (scenario two).

**Table 5. Graded Veneer Recovery Percentage when Effective Pruning is Simulated**

<table>
<thead>
<tr>
<th>Species</th>
<th>Grade recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-grade</td>
</tr>
<tr>
<td><em>Corymbia citriodora</em> subsp. <em>variegata</em></td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>(0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td>(0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus dunnii</em></td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td>(0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus pellita</em></td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td>(0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td>(0.0)</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>(0.0)</td>
</tr>
</tbody>
</table>

Note: The change in graded veneer recovery is provided in parenthesis.

*Eucalyptus nitens* achieved by far the most gain from this scenario with 62% of veneer achieving assigned grades of C-grade or better, and therefore well exceeded the target grade quality proportions nominated by the Engineered Wood Products Association of Australasia (30% to 40%) as necessary for commercial production of a standard mix of saleable structural panel products. Recovery of *E. cloeziana* C-grade and better veneers increased to 47%, while *C. citriodora* subsp. *variegata* increased to 31% recovery of C-grade veneers or better. All remaining species still failed to produce sufficient proportions of C-grade of better veneer. *Eucalyptus dunnii* had the least improvement, with 22% of veneers achieving C-grade or better. This species had small average billet diameter and was clearly limited by gum pockets, two factors which prevented the pruning scenario from achieving higher grade improvements. The same trend was demonstrated with *C. citriodora* subsp. *variegata*; however, this species had a reasonable proportion of C-grade veneers before applying the pruning scenario.

These gains are greater than the grade quality difference that was reported by Blakemore *et al.* (2010) for a small study that included five pruned and five unpruned *E. nitens* trees. In this study, the changes in percentage recoveries with pruned billets compared with unpruned billets were: A-grade +5.7%; B-grade +3.1%; C-grade +3.8%; D-grade +0.5%, and reject grade -13.1%. It should be noted however, that the veneer quality from the unpruned trees was already much higher than presented in Table 5, with over 50% of the resulting veneer achieving C-grade or better. Moreover, the trees sampled by Blakemore *et al.* (2010) were bigger (mean diameter of 50.6 cm) than in this study, and the peeling and grading methods were different, making any comparison between the studies speculative.
Tables 6 illustrates the impact on grade recovery that can be possible if both scenarios (i.e., one and two) are combined, leading to a shift in permissible grade limits for gum pockets and gum veins, with effective pruning.

**Table 6. Graded Veneer Recovery Percentage with Gum Upgrade Combined with Effective Pruning**

<table>
<thead>
<tr>
<th>Species</th>
<th>Grade recovery</th>
<th>A-grade</th>
<th>B-grade</th>
<th>C-grade</th>
<th>D-grade</th>
<th>Rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corymbia citriodora subsp. variegata</strong></td>
<td></td>
<td>0.5%</td>
<td>15.8%</td>
<td>64.1%</td>
<td>16.8%</td>
<td>2.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0)</td>
<td>(14.0)</td>
<td>(46.2)</td>
<td>(-56.8)</td>
<td>(-3.4)</td>
</tr>
<tr>
<td><strong>Eucalyptus cloeziana</strong></td>
<td></td>
<td>0.3%</td>
<td>16.6%</td>
<td>61.2%</td>
<td>19.9%</td>
<td>2.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0)</td>
<td>(10.5)</td>
<td>(32.4)</td>
<td>(-40.2)</td>
<td>(-2.7)</td>
</tr>
<tr>
<td><strong>Eucalyptus dunnii</strong></td>
<td></td>
<td>0.0%</td>
<td>3.2%</td>
<td>60.6%</td>
<td>35.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0)</td>
<td>(2.7)</td>
<td>(44.6)</td>
<td>(-44.0)</td>
<td>(-3.3)</td>
</tr>
<tr>
<td><strong>Eucalyptus pellita</strong></td>
<td></td>
<td>0.1%</td>
<td>18.7%</td>
<td>60.8%</td>
<td>18.0%</td>
<td>2.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0)</td>
<td>(14.1)</td>
<td>(50.2)</td>
<td>(-62.0)</td>
<td>(-2.3)</td>
</tr>
<tr>
<td><strong>Eucalyptus nitens</strong></td>
<td></td>
<td>0.4%</td>
<td>31.7%</td>
<td>33.0%</td>
<td>32.1%</td>
<td>2.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0)</td>
<td>(20.6)</td>
<td>(17.8)</td>
<td>(-35.6)</td>
<td>(-2.8)</td>
</tr>
<tr>
<td><strong>Eucalyptus globulus</strong></td>
<td></td>
<td>0.0%</td>
<td>6.5%</td>
<td>45.2%</td>
<td>42.4%</td>
<td>5.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0)</td>
<td>(5.4)</td>
<td>(42.5)</td>
<td>(-41.9)</td>
<td>(-6.0)</td>
</tr>
</tbody>
</table>

Note: The change in graded veneer recovery is provided in parenthesis.

The results of this scenario showed a substantial improvement for all species. *Eucalyptus nitens* achieved the lowest improvement, which was a result of the minimal gains from the gum defect limitation change; however, this still resulted in 65% of veneer achieving C-grade or better. *Eucalyptus nitens* also achieved the highest recovery of B-grade, with 32% recovered under this scenario. *Corymbia citriodora subsp. variegata, E. pellita,* and *E. cloeziana* all achieved similar impressive recoveries of C-grade veneer or better, with 81%, 80%, and 78% being recovered, respectively, for C-grade and better. *Eucalyptus nitens* and *E. dunnii* achieved 65% and 64%, respectively, while *E. globulus* achieved 52%. It is important to note that splits and compression are clearly limiting further grade improvement under this scenario. This observation confirms the adverse effect of high levels of growth stresses on veneer grade recovery for these species.

The results demonstrate that while scenarios one and two each had a positive effect individually, combining them had a dramatic effect, beyond a simply additive effect on increasing the veneer grade. Modifying the grade limitations relating to gum pockets and gum veins in line with the scenario one is potentially relatively easy with minimal investment required and can therefore be implemented quickly. A market analysis will need to be conducted to determine the true possibility of this scenario being commercially adopted and may need to be product specific. Implementing and achieving effective pruning is more complex, and an economic analysis will be required to determine its profitability. In addition, for the pruning to be truly effective, pruning practices and procedures will need to be perfected to ensure the grade quality benefits are able to be realised.

Table 7 illustrates the impact on grade recovery when gum upgrading (scenario one) and effective pruning (scenario two) are combined, similar to scenario three, however, with a less conservative grade upgrading strategy allowing 25% of B-grade veneers resulting from the scenario being further upgraded to A-grade.
Table 7. Graded Veneer Recovery Percentage with Gum Upgrade Combined with Effective Pruning and Additional Grade Upgrading

<table>
<thead>
<tr>
<th>Species</th>
<th>Grade recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A-grade</td>
</tr>
<tr>
<td>Corymbia citriodora subsp. variegata</td>
<td>4.5%</td>
</tr>
<tr>
<td></td>
<td>(4.0)</td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td>4.5%</td>
</tr>
<tr>
<td></td>
<td>(4.2)</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>0.8%</td>
</tr>
<tr>
<td></td>
<td>(0.8)</td>
</tr>
<tr>
<td>Eucalyptus poliita</td>
<td>4.7%</td>
</tr>
<tr>
<td></td>
<td>(4.6)</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td>8.3%</td>
</tr>
<tr>
<td></td>
<td>(7.9)</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>1.6%</td>
</tr>
<tr>
<td></td>
<td>(1.6)</td>
</tr>
</tbody>
</table>

Note: The change in graded veneer recovery is provided in parenthesis.

Economic Impact

Table 8 shows the increase in relative value resulting from gum upgrade (scenario one), effective pruning (scenario two), gum upgrade combined with effective pruning (scenario three), and further grade improvements from gum upgrading combined with effective pruning grade upgrading (scenario four) with resource only as the baseline (as graded to Australian and New Zealand Standard AS/NZS 2269.0:2012 (Standards Australia 2012)).

Table 8. Change in Relative Veneer Value with the Adoption of the Four Grade Scenarios

<table>
<thead>
<tr>
<th>Species</th>
<th>Gum defects upgraded (scenario 1)</th>
<th>Effective pruning (scenario 2)</th>
<th>Gum defects upgraded and effective pruning (scenario 3)</th>
<th>Gum defects upgraded and effective pruning with 25% of B-grade upgraded to A-grade (scenario 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corymbia citriodora subsp. variegata</td>
<td>4.6</td>
<td>9.8</td>
<td>18.2</td>
<td>21.5</td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td>3.3</td>
<td>8.1</td>
<td>13.5</td>
<td>17.2</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>5.2</td>
<td>4.1</td>
<td>12.4</td>
<td>13.3</td>
</tr>
<tr>
<td>Eucalyptus poliita</td>
<td>2.6</td>
<td>6.9</td>
<td>18.0</td>
<td>21.9</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td>0.3</td>
<td>15.3</td>
<td>16.3</td>
<td>22.6</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>0.3</td>
<td>11.3</td>
<td>17.0</td>
<td>18.6</td>
</tr>
</tbody>
</table>

Scenario one, which included the upgrading of gum veins and gum pockets, resulted in small gains in relative veneer value for the sub-tropical and tropical species of between 2.6% and 5.2%. The temperate species (E. nitens and E. globulus) achieved minimal gains of 0.3%. As discussed, these gains can potentially be realised quickly and with minimal investment.

Scenario two included the adoption of effective pruning, with the temperate species being the main beneficiaries with increases of relative veneer value of
between 11.3 and 15.3%. The sub-tropical and tropical species resulted in modest relative veneer value gains of between 4.1% and 9.8%. A comprehensive economic analysis will be required to determine the true change in profitability as the implementation of this scenario will incur additional costs during the early phases of the plantation growth which have not been considered in this analysis.

In this scenario, except for *C. citriodora* subsp. *variegata*, the total change in value clearly depends on the billet diameter as shown in Fig. 7. Indeed, the greater the diameter of the billet, the higher the volume of wood without knots and knot-related defects. The exception is explained by defects other than knot and knot-related defects, such as splits, which were minimal in *C. citriodora* subsp. *variegata* (6%) compared to *E. dunnii* (28%) despite having similar average diameters (Table 2). This observation indicates that after gum, knots, and knot-related defects, growth stress-related defects (i.e., splitting or compression) are a major cause of veneer downgrade.

![Graph showing relationship between average billet diameter and change in total value when effective pruning is performed](image)

**Fig. 7.** Relationship between average billet diameter and change in total value when effective pruning is performed (scenario two)

Scenario three delivered further improvements in relative veneer value with increases between 12.4% and 18.2%. *Eucalyptus dunnii* and *E. cloeziana* displayed the smallest improvement in value, which was influenced by their smaller average billet diameter, which impacts on the recovery of higher grades after pruning.

Scenario four produced the highest gains in relative veneer value with increases up to 22.6%. Because of the non-linear increase in value from lower grades to higher grades, determining the relative total veneer value was very sensitive to the proportion of veneers in higher veneer grades. As a matter of fact, the A-grade value was three times the value of D-grade veneer and almost twice the value of B-grade veneer.
CONCLUSIONS

1. The study demonstrated that processing Australian hardwood from plantations using spindleless veneer lathe technology produced graded veneer recoveries dominated by D-grade veneer across all species. Although D-grade veneer is technically suitable for face veneers for some 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), which are more demanded for face veneers, will make the commercial production of a standard mix of saleable structural panel products challenging if relying on this resource alone.

2. The veneers contained a range of defects that impacted the final assigned grade. The presence of gum pockets had the highest impact with up to 70% of veneer being limited to D-grade for *C. citriodora* subsp. *variegata*, *E. cloeziana*, *E. dunnii*, and *E. pellita*. Gum pockets were the second-ranked defect for *E. globulus*. For *E. globulus*, the occurrence of bark pockets or decay, mainly surrounding knots, was the main defect limiting veneer to D-grade. Encased knots contributed to limiting veneer grades to D-grade, especially for *E. nitens*, *E. pellita*, and *E. globulus* veneers. Veneer surface roughness resulted in up to 36% of veneers being restricted to D-grade, and veneer splits also impacted grade recovery (up to 28% of veneer limited to D-grade). Other defects contributed to a lesser degree.

3. The simulation of a scenario upgrading gum pockets and gum veins to C-grade and B-grade resulted in an increased recovery of C-grade and better veneers across all species. This scenario enabled 52% of *E. cloeziana*, 45% of *C. citriodora* subsp. *variegata*, and 41% of *E. dunnii* veneers to achieve assigned grades of C-grade or better. This exceeds the quality proportions delineated by the Engineered Wood Products Association of Australasia (30% to 40% of assigned C-grade and better) as necessary for commercial production of structural panel products. Modifying the grade limitations related to gum defects is potentially easy with minimal investment and can be implemented relatively quickly.

4. Grade scenario two simulated effective pruning. This improved higher grade recoveries for all species. *Eucalyptus nitens* achieved the most gain from this scenario with 62% of veneer achieving assigned grades of C-grade or better. *Eucalyptus cloeziana* recovery increased to 47%, while *C. citriodora* subsp. *variegata* increased to 31% recovery of C-grade veneers or better. These three species therefore meet or exceed the target assigned grade quality proportions nominated by the Engineered Wood Products Association of Australasia (30% to 40% of assigned C-grade and better) as necessary for commercial production of structural panel products. Implementing and achieving effective pruning can be complex and an economic analysis will be required to determine its profitability.

5. Combining gum defects upgrade and effective pruning had a substantial impact on achieving higher grade veneer qualities, beyond a simply additive effect on increasing the veneer grade. With this scenario, all species produced C-grade and better grade recoveries exceeding the target grade quality proportions nominated by the Engineered Wood Products Association of Australasia (30% to 40% of assigned C-grade and better).

6. Reducing the impact of gum defects has the potential to increase the relative veneer values between 0.3% and 5.2%, depending on species. Improving the
resulting grade quality of veneer through effective pruning has the potential to increase relative veneer values between 4.1% and 15.3%. Combining both scenarios produced the best increase in relative veneer value with increases between 12.4% and 18.2% and between 13.3% and 22.6% with further grade improvements from gum and pruning upgrading.

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CHAPTER 4: Variation in rotary veneer recovery from Australian plantation *Eucalyptus globulus* and *Eucalyptus nitens*

Variation in Rotary Veneer Recovery from Australian Plantation *Eucalyptus globulus* and *Eucalyptus nitens*

Robert L. McGavin,a,b,⁎ Henri Bailleres,b Matthew Hamilton,c David Blackburn,c Mario Vega,c and Barbara Ozarska,a

The processing of Australian plantation-grown *Eucalyptus globulus* and *E. nitens* into rotary veneer was shown to produce acceptable recoveries. Three plantation sites for each species were sampled. Silvicultural treatments (thinning and pruning) and growing environments varied between sites. Graded veneer recoveries were dominated by D-grade veneer across all six sites. Variation between the *E. nitens* sites was evident, with recoveries differing between sites reflecting silvicultural treatments. However, only minimal variation in recovery was shown between the *E. globulus* sites. The presence of similar levels of defects across all *E. globulus* sites indicates that the intensive silvicultural management at one site studied was not effective in the production of clear wood, and may possibly have adversely affected grade recovery. Veneer value analysis demonstrated only minimal differences between *E. globulus* sites. More variation was observed in the *E. nitens* value analysis; however, intensive silvicultural management implemented did not necessarily result in higher veneer value.

Keywords: *Eucalyptus*; Veneer; Hardwood; Plantation; Processing; Grade quality; Recovery; Silviculture; Pruning; Thinning

Contact information: a: University of Melbourne, Department of Forest Ecosystem Science, 500 Yarra Boulevard Richmond, Victoria 3121 Australia; b: Queensland Department of Agriculture, Fisheries and Forestry, Horticulture and Forestry Science, Salisbury Research Facility, 50 Evans Road, Salisbury, Queensland 4107 Australia; c: School of Biological Sciences and National Centre for Future Forest Industries, University of Tasmania, Private Bag 55, Hobart, Tasmania 7001 Australia; *Corresponding author: robbie.mcgavin@daff.qld.gov.au*

INTRODUCTION

The establishment of commercial hardwood plantation forests in Australia has seen rapid expansion in recent decades. Gavran (2013) reported that over two million hectares of plantation forestry now exists in Australia, of which about one million are hardwood species. While the industry’s softwood sector in Australia has become well-established with reliance on a plantation resource, the hardwood sector remains largely dependent on native forests for log supply, especially for value-added products, including sawn timber and engineered wood products. With increasing limitations preventing access to some native forest areas, as well as the increasing availability of maturing hardwood plantations, interest exists from the processing sector as to the quality and suitability of plantation wood for value-added products. In addition, plantation growers are continuously seeking the processing streams and end uses that can provide the highest return from their plantations.

Of the one million-hectare hardwood estate, *Eucalyptus globulus* and *E. nitens* dominate (55% and 24%, respectively), with over three quarters of the plantation estate
growing these two species (Gavran 2013). Small areas of some plantations have been established and managed with a high-value product focus. Wood et al. (2009) reported approximately 26,000 hectares of plantations principally located in Tasmania, which are predominantly *E. nitens* plantations that have been thinned, pruned, and managed for higher-value end-uses. The majority of the estate, however, has been managed for pulpwood markets and is dominated by trees selected primarily by pulpwood properties, and which are therefore mostly unthinned and unpruned. The result is a plantation estate that contains forest and wood qualities that are most likely not optimal for higher-value products. Understanding the quality and variability of the new resource is critical for the wood processing sector’s ability to adapt and plan for the future.

Despite the original plantation establishment and management intent, less than favourable market conditions for Australian hardwood pulpwood have prompted the exploration of alternative higher-value markets. As reported by McGavin et al. (2014a), the processing of Australian-grown hardwood plantations into veneer using relatively new spindleless veneer lathe technology has the potential to produce veneer recoveries that are more favourable when compared with solid wood processing techniques.

While the veneer recoveries reported by McGavin et al. (2014a) were high, the grade recoveries were dominated by D-grade veneers when graded to Australian and New Zealand Standard AS/NZS 2269.0:2012 (Standards Australia 2012). The low recovery of higher-grade veneers (C-grade and better) was identified by McGavin et al. (2014a, b) as a challenge for commercial panel production with insufficient proportions of face veneer qualities to allow a standard commercial mix of structural panel products to be manufactured when using only a resource of this quality.

Defects such as bark and decay, encased knots, gum pockets, veneer splits, veneer roughness, and veneer compression were reported by McGavin et al. (2014b) as the main contributing defects that cause high proportions of *E. globulus* and *E. nitens* veneer to be restricted to D-grade, the lowest grade described within AS/NZS 2269.0:2012 (Standards Australia 2012).

The analyses reported by McGavin et al. (2014a, b) were performed on semi-commercial batches and reported at the species level to provide an overview of the performance of plantation estate eucalypt species. The two species examined in these studies have been previously shown to be genetically stable in different environments (Callister et al. 2011; Blackburn et al. 2014). Strong race stability and inter-site additive genetic correlations for additive effects in the traits examined were also high, indicating a lack of genotype x environmental interaction at the family level. The overall findings suggest that any significant variation in growth (and therefore associated veneer grade quality traits such as splitting and compression) can mainly be attributed to the stand’s silvicultural management and the growing environment in that rotation period.

The objective of this study was to analyse the variation in veneer recoveries, including the defect assessment of veneer produced from a range of mid-rotation *E. globulus* and *E. nitens* plantations. The selected plantations under study represent a range of site qualities and management regimes (e.g., thinning and pruning). The resulting analysis will contribute to the understanding of the quality and variability of the current *E. globulus* and *E. nitens* plantation resources, as well as offer guidance on future plantation management strategies.
EXPERIMENTAL

Plantation Sampling

Plantation trees were sourced from a total of six different sites (three sites for each species), representing a range of site qualities and management regimes (Table 1). The *E. globulus* plantations were located at Deans Marsh, Orford, and Mumbannar in Victoria, while the *E. nitens* plantations were located at Strathblane, Geeveston, and Florentine in Tasmania. Selected trees were representative of diameter at breast height over bark (DBHOB) and form of the surrounding plantation trees most likely to be suitable for veneer or solid wood processing (Table 2). From each selected tree, two 2-m logs were removed from between 0.5 m to 2.5 m and 3.7 m to 5.7 m. Each log was docked to 1.3 m immediately before peeling. The merchandising and docking strategy adopted aimed to simulate the common commercial practice of minimising the time between final billet docking and veneer processing. This is achieved in the industry by maintaining long log lengths after harvesting and only merchandising into billets immediately before processing. The 2 m log sections provided sufficient additional length which was sacrificed to allow the 1.3 m billets to be docked immediately before processing. This removed any degrade from the ends that resulted from the delay between harvesting and veneer processing.

**Table 1. Plantation Management History**

<table>
<thead>
<tr>
<th>Species</th>
<th>Plantation Location</th>
<th>Planting Year</th>
<th>Establishment at Stocking (Stems per Hectare)*</th>
<th>Age at Thinning (Years)*</th>
<th>Age at Pruning (Years)**</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Deans Marsh, Victoria (38°39'S, 143°92'E)</td>
<td>1997</td>
<td>1000</td>
<td>4 and 10 (250 and 190)</td>
<td>4 and 6 (4.5 and 6.5)</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Orford, Victoria (38°21'S, 142°07'E)</td>
<td>2000</td>
<td>1190</td>
<td>No thinning</td>
<td>No pruning</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Mumbannar, Victoria (37°96'S, 141°22'E)</td>
<td>2000</td>
<td>1000</td>
<td>No thinning</td>
<td>No pruning</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Strathblane, Tasmania (43°38'S, 146°94'E)</td>
<td>1993</td>
<td>1250</td>
<td>11 (314)</td>
<td>3 to 4 and 5 (2.5 and 4.5)</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Geeveston, Tasmania (43°15'S, 146°84'E)</td>
<td>1991</td>
<td>1333</td>
<td>10 (192)</td>
<td>4 to 6 (up to 6.4)</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Florentine, Tasmania (42°66'S, 146°47'E)</td>
<td>1993</td>
<td>1250</td>
<td>No thinning</td>
<td>No pruning</td>
</tr>
</tbody>
</table>

* Retained stocking (stems per hectare) presented in parentheses
** Pruned height (metres) presented in parentheses

Table 2. Plantation Trial Material

<table>
<thead>
<tr>
<th>Species</th>
<th>Plantation Location</th>
<th>Age (Years)</th>
<th>Number of Trees</th>
<th>Average DBHOB of Plantation Trees * (cm)</th>
<th>Average DBHOB of Selected Trees * (cm)</th>
<th>Thinned and Pruned</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Deans Marsh, Victoria</td>
<td>16</td>
<td>20</td>
<td>37.0 (4.9)</td>
<td>33.8 (2.6)</td>
<td>Yes</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Orford, Victoria</td>
<td>13</td>
<td>20</td>
<td>22.2 (5.7)</td>
<td>29.5 (3.2)</td>
<td>No</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>Mumbannar, Victoria</td>
<td>13</td>
<td>20</td>
<td>21.0 (9.8)</td>
<td>28.5 (2.9)</td>
<td>No</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Strathblane, Tasmania</td>
<td>20</td>
<td>20</td>
<td>31.3 (6.0)</td>
<td>30.0 (3.4)</td>
<td>Yes</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Geeveston, Tasmania</td>
<td>22</td>
<td>10</td>
<td>43.1 (10.7)</td>
<td>42.0 (9.8)</td>
<td>Yes</td>
</tr>
<tr>
<td><em>Eucalyptus nitens</em></td>
<td>Florentine, Tasmania</td>
<td>20</td>
<td>11</td>
<td>26.9 (11.1)</td>
<td>33.8 (2.6)</td>
<td>No</td>
</tr>
</tbody>
</table>

* Standard deviation presented in parentheses

Billet Assessment

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

- Large end diameter under bark, \( LEDUB \) (m)—measured from the circumference with a diameter tape;
- Small end diameter under bark, \( SEDUB \) (m)—measured from the circumference with a diameter tape; and
- Sweep, \( S \) (m)—measured as the maximum deviation from a straight edge that bridges the ends of the 1.3-m billets.

From the measured data, billet volumes were derived following the methodology adopted by McGavin et al. (2014a).

Billet Processing

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 a maximum log diameter of 400 mm. The minimum peeler core size was 45 mm. Twelve *E. nitens* billets from the Geeveston site, which were too large (> 400-mm diameter) to directly process on the spindleless lathe were rounded and/or partially peeled using a conventional spindled lathe before the peeling was completed on the spindleless lathe. For the study, the lathe settings and log conditioning were fixed, and the nominal dried veneer thickness was 2.5 mm.

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 practise. Veneer widths as narrow as 300 mm were included, while veneer sheets narrower than 300 mm were discarded. Veneer sheets were labelled with a unique identifier. Clipped veneer was seasoned using a conventional jet box veneer drying system using standard commercial practices (temperatures ranged from 160 to 190 °C during drying), with a target moisture content of 5%. Veneers were then stabilised to 10% moisture content in storage.
A more detailed description of the methodology regarding billet preparations and processing is described by McGavin et al. (2014a).

**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 visual grading classification systems. The standard separates structural veneer into four veneer surface qualities and a reject grade according to the severity and concentration of imperfections and defects.

To facilitate comparisons between species and sites, only resource-related defects have been included in this analysis. Defects that could be directly attributed to the veneering process, such as splitting caused by veneer handling, have been excluded from the analysis so as to not disadvantage any particular species or site that may benefit from a further refined process. For each veneer, the visual grade was recorded for each type of defect present within the veneer. This allowed the analysis of the impact of each type of defect in terms of its contribution to the assigned grade of each veneer. The defects that caused the lowest visual grade were identified as grade-limiting defects, and the resulting assigned grade was recorded for each veneer. The grading process was undertaken by a minimum of two experienced graders to minimise variation with defect definition and measurement, as well as to ensure consistent assessment.

**Recovery**

Four recovery calculations following the same methodology as detailed by McGavin et al. (2014a) were made to determine green veneer recovery, gross veneer recovery, net veneer recovery, and graded veneer recovery.

Green veneer recovery was calculated using average green veneer thickness; green veneer width (perpendicular to grain) as measured prior to clipping and excluded any major defects (i.e., wane or undersize thickness) that were present at the beginning or end of the veneer ribbon; veneer length (same as billet length); and billet volume.

Gross veneer recovery was calculated using average dry veneer thickness; veneer width (perpendicular to grain) of dried veneer that met the grade requirements of A-grade, B-grade, C-grade, and D-grade in accordance with AS/NZS 2269.0:2012; veneer length (same as billet length); and billet volume.

Net veneer recovery was calculated as the gross veneer recovery minus a trimming factor. Graded veneer recovery was the net grade recovery separated into individual grades (A-grade, B-grade, C-grade, and D-grade) expressed as a proportion of net recovered volume. Veneers that did not meet these grade requirements were labelled reject grade (F-grade).

**Relative Veneer Value**

Accurate commercial veneer values for the species included in the study are difficult to determine; however, to provide an indication of the economic impact that the different species and plantation sites had on veneer value, relative values for each grade were provided by the Engineered Wood Products Association of Australasia (2014). This suggests that C-grade veneer attracts a value 1.2 times higher than D-grade, B-grade attracts a value 1.7 times than D-grade, and A-grade attracts a value three times higher
than D-grade. Reject grade is considered of no value. This analysis focuses on the ratios of veneer grades recovered and discounts for the variation in veneer volume recovered.

**RESULTS AND DISCUSSION**

**Visual Grading**

A total of 202 billets (16.4 m³) from six different hardwood plantations were processed using a spindleless lathe, which produced 3,097 m³ of rotary veneer. Table 3 provides details of the billet characteristics for each site.

**Table 3. Billet Characteristics of the Six Hardwood Plantation Sites**

<table>
<thead>
<tr>
<th>Plantation Location</th>
<th>Species</th>
<th>Thinned and Pruned</th>
<th>Average Billet Small-end Diameter under Bark (cm)</th>
<th>Average Billet Volume (m³)</th>
<th>Total Volume Processed (m³)</th>
<th>Average Sweep (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deans Marsh</td>
<td><em>Eucalyptus globulus</em></td>
<td>Yes</td>
<td>28.4 (3.2)</td>
<td>0.088 (0.019)</td>
<td>3.517</td>
<td>12 (5.0)</td>
</tr>
<tr>
<td>Orford</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>24.8 (2.7)</td>
<td>0.067 (0.015)</td>
<td>2.661</td>
<td>10 (5.4)</td>
</tr>
<tr>
<td>Mumbannar</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>23.8 (2.7)</td>
<td>0.062 (0.015)</td>
<td>2.482</td>
<td>11 (5.3)</td>
</tr>
<tr>
<td>Strathblane</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>24.6 (3.1)</td>
<td>0.067 (0.017)</td>
<td>2.663</td>
<td>8 (4.8)</td>
</tr>
<tr>
<td>Geeveston</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>36.6 (9.2)</td>
<td>0.152 (0.074)</td>
<td>3.039</td>
<td>6 (3.2)</td>
</tr>
<tr>
<td>Florentine</td>
<td><em>Eucalyptus nitens</em></td>
<td>No</td>
<td>29.6 (2.5)</td>
<td>0.094 (0.017)</td>
<td>2.075</td>
<td>8 (3.9)</td>
</tr>
</tbody>
</table>

*Standard deviation presented in parentheses.*

The measured veneer recoveries are displayed in Table 4.

**Table 4. Veneer Recoveries**

<table>
<thead>
<tr>
<th>Plantation Location</th>
<th>Species</th>
<th>Thinned and Pruned</th>
<th>Green Recovery (%)</th>
<th>Gross Recovery (%)</th>
<th>Gross Recovery Percentage of Green Recovery (%)</th>
<th>Net Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deans Marsh</td>
<td><em>Eucalyptus globulus</em></td>
<td>Yes</td>
<td>77</td>
<td>56</td>
<td>73</td>
<td>49</td>
</tr>
<tr>
<td>Orford</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>77</td>
<td>58</td>
<td>77</td>
<td>51</td>
</tr>
<tr>
<td>Mumbannar</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>77</td>
<td>59</td>
<td>77</td>
<td>52</td>
</tr>
<tr>
<td>Strathblane</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>76</td>
<td>64</td>
<td>84</td>
<td>56</td>
</tr>
<tr>
<td>Geeveston</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>74</td>
<td>61</td>
<td>82</td>
<td>54</td>
</tr>
<tr>
<td>Florentine</td>
<td><em>Eucalyptus nitens</em></td>
<td>No</td>
<td>76</td>
<td>61</td>
<td>79</td>
<td>54</td>
</tr>
</tbody>
</table>

All sites achieved similar green veneer recoveries of between 74% and 77%. The *E. globulus* sites achieved gross recoveries of between 56% and 59%, with Deans Marsh achieving the lowest gross recovery value (56%), despite receiving the most intensive silvicultural management. The *E. nitens* sites achieved higher gross recoveries of between 61% and 64%, with the Strathblane site achieving the highest gross recovery (64%). Geeveston and Florentine both achieved gross recoveries of 61%. The net recoveries are proportional to the gross recovery values.

The recoveries measured in this study are high compared to most previous studies in Australia when rotary peeling eucalypt species. For example, Thomas *et al.* (2009) reported green off-lathe recoveries for plantation *E. dunnii* (aged between 12 and 34 years-old) ranging from 35% to 45%. Blakemore *et al.* (2010) reported similar recovery values for a small-scale *E. nitens* (21-year-old) veneering trial. The difference in recoveries between the previous studies and this study is probably attributed to the application of traditional technologies (spindled lathe), which produce larger diameter peeler cores and failed peeling due to spindle grip problems (*e.g.*, core splitting). Different veneer grading methods also help explain the variation.

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 in China. While adopting spindless lathe technology, similar to this study, the comparatively low green veneer recovery observed is likely attributable to a lower average small-end diameter of the billets (112 mm). The recoveries are comparable to those reported by McGavin *et al.* (2014a) using similar processing technologies and methodologies to this study, for the assessment of six Australian hardwood plantation species.

There was no relationship between billet SEDUB and veneer recovery because of the compounding influences of billet geometry (*i.e.*, sweep, taper, ovality, and surface irregularities) and billet end splitting, as well as billet core defects, which influence the residual peeler core diameter (McGavin *et al.* 2014a).

Table 5 provides details of the grade recovery (recovered veneer for each grade as a proportion of total veneer surface area) for each site.

**Table 5. Graded Veneer Recovery (Recovered Veneer for Each Grade as a Proportion of Total Veneer Surface Area)**

<table>
<thead>
<tr>
<th>Plantation Location</th>
<th>Species</th>
<th>Thinned and Pruned</th>
<th>A-grade Recovery (%)</th>
<th>B-grade Recovery (%)</th>
<th>C-grade Recovery (%)</th>
<th>D-grade Recovery (%)</th>
<th>Reject Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deans Marsh</td>
<td><em>Eucalyptus globulus</em></td>
<td>Yes</td>
<td>0.0</td>
<td>1.3</td>
<td>3.4</td>
<td>80.7</td>
<td>14.6</td>
</tr>
<tr>
<td>Orford</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>0.0</td>
<td>1.1</td>
<td>2.3</td>
<td>86.5</td>
<td>10.1</td>
</tr>
<tr>
<td>Mumbannar</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>0.0</td>
<td>0.9</td>
<td>2.0</td>
<td>87.1</td>
<td>10.0</td>
</tr>
<tr>
<td>Strathblane</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>1.1</td>
<td>22.9</td>
<td>20.8</td>
<td>52.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Geeveston</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>0.1</td>
<td>7.4</td>
<td>17.1</td>
<td>64.9</td>
<td>10.5</td>
</tr>
<tr>
<td>Florentine</td>
<td><em>Eucalyptus nitens</em></td>
<td>No</td>
<td>0.0</td>
<td>0.5</td>
<td>4.6</td>
<td>93.1</td>
<td>1.8</td>
</tr>
</tbody>
</table>

* Recovered grade veneer as a proportion of veneer surface area

Despite the Deans Marsh site having intensive silvicultural management, implemented to increase proportions of higher-quality end-products, there was minimal difference in the spread of veneer grades. The D-grade recovery was less for the Deans Marsh site compared with the two unthinned and unpruned *E. globulus* sites at Orford and Mumbannar; however, the recovery of reject grade was higher, resulting in minimal improvement being observed in higher-grade qualities (C-grade and better). This explains the lower gross recovery observed for Deans Marsh in comparison with the other two sites (Table 4), which had comparable graded veneer recoveries. The spread of grade recoveries are consistent with other similar studies, such as Peng et al. (2014), who reported over 80% of eucalypt hybrid veneers being categorised as D-grade (although based on a slightly different grading standard), and less than 3% of veneers meeting the grade requirements of C-grade or better (with the balance being reject grade).

A greater variation was shown in grade recoveries between the three *E. nitens* sites. The Florentine site, which was not thinned or pruned, was almost totally dominated by D-grade veneer (93.1%), and as expected, the thinned and pruned Strathblane and Geeveston sites achieved an improved spread of recoveries across higher-grade qualities when compared with the Florentine site. Of the three *E. nitens* sites, the Strathblane site performed best, with superior recovery of higher grades (C-grade and better). For example, the Strathblane site achieved three times more B-grade veneer than the Geeveston site, despite the latter being thinned and pruned and having the largest diameter billets. The Geeveston site yielded a higher reject recovery (10.5%), which was three to five times higher than the other two *E. nitens* sites (1.8% and 2.8%, respectively).

The Engineered Wood Products Association of Australasia (2013) suggests that the rotary veneer industry requires approximately 30% to 40% of their graded veneer production to be at least C-grade or better to enable saleable product manufacture. The Strathblane site was the only site to achieve this benchmark, with 45% of veneer meeting the grade requirements of C-grade or better.

Table 6 illustrates the five highest-ranked defects (in order of severity) that prevented veneers from attaining grades higher than D-grade for each site.

All six sites were impacted by similar defects. Bark pockets or decay, mostly surrounding knots, was the highest-ranked grade-limiting defect in five of the six sites, and it ranked second in the remaining site. While highly ranked, the impact was more severe for *E. globulus*. The presence of these defects in the peeled veneer supports the findings of previous research studies, which have shown that these species may not heal well after pruning or self-pruning, with the section of stem-wood laid down post-pruning being prone to decay entry and slow occlusion (Wardlaw and Neilson 1999; Pinkard 2002; Pinkard et al. 2004; Deflorio et al. 2007).

Encased knots also featured heavily across all sites, although they had less impact in the thinned and pruned *E. nitens* sites (Strathblane and Geeveston). Despite the Deans Marsh *E. globulus* site also being thinned and pruned, there was little benefit gained when compared with results from the unthinned and unpruned *E. globulus* sites. Instead of the veneer of the pruned billets being knot-free (at least from the pruned diameter plus an allowance for branch occlusion), the tree seems to have not been effective in producing knot- (and knot-related defects-) free wood; rather, the branch stubs produced a deficient occlusion pattern (along with a high proportion of gum pockets) as the tree grew.
Table 6. Top Five Ranked Defects Preventing Veneers from Attaining Assigned Grades Higher than D-grade

<table>
<thead>
<tr>
<th>Plantation Location</th>
<th>Species</th>
<th>Thinned and Pruned</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Deans Marsh</td>
<td>Eucalyptus globulus</td>
<td>Yes</td>
<td>Bark or decay (85%)</td>
</tr>
<tr>
<td>Orford</td>
<td>Eucalyptus globulus</td>
<td>No</td>
<td>Bark or decay (82%)</td>
</tr>
<tr>
<td>Mumbannar</td>
<td>Eucalyptus globulus</td>
<td>No</td>
<td>Bark or decay (93%)</td>
</tr>
<tr>
<td>Strathblane</td>
<td>Eucalyptus nitens</td>
<td>Yes</td>
<td>Bark or decay (36%)</td>
</tr>
<tr>
<td>Geeveston</td>
<td>Eucalyptus nitens</td>
<td>Yes</td>
<td>Bark or decay (43%)</td>
</tr>
<tr>
<td>Florentine</td>
<td>Eucalyptus nitens</td>
<td>No</td>
<td>Encased knots (86%)</td>
</tr>
</tbody>
</table>

Note: The proportion of veneer impacted by each defect is provided in parentheses.

Gum pockets ranked highly for the *E. globulus* sites. As suggested by McGavin et al. (2014b), the size of this defect was often small and concentrated, and while it would influence the appearance of the veneer, it would be expected to have a negligible effect on mechanical properties or on the panel manufacturing process. The characteristics of this defect in the veneer are such that it may be unnecessarily severe to downgrade such quantities of veneer to D-grade, especially when compared with other appearance-affecting defects, which are permissible in higher grades. A market acceptance analysis and review of the permissible limits outlined in the grading standards for this defect could be beneficial.

Veneer surface roughness ranked either third or fourth for preventing veneer from all sites from attaining a grade higher than D-grade. Veneer surface roughness is mostly present in areas of veneer where there is grain deviation present, such as around knots and knot holes. This was supported by the fact that surface roughness has more impact on *E. globulus* veneers, which also reported a higher severity of encased knots when compared with *E. nitens*. McGavin et al. (2014b) reported a significant (p<0.001) and positive, although relatively weak correlation between sound or encased knot rank and veneer surface roughness rank.

Splits ranked third for the Geeveston and Florentine *E. nitens* sites. While splits ranked fourth for Strathblane, splits only prevented 5% of veneers from attaining a grade higher than D-grade for this site. Splits fell outside the top five ranked defects (Table 6) for *E. globulus* sites; however, splits were responsible for between 10% and 15% of veneers’ inability to attain a grade higher than D-grade.

Compression in the *E. globulus* veneer (ranked fifth) resulted in 25% to 35% of veneer being restricted to D-grade. This defect was much more obvious when the veneer
was dried, with many veneers being “rippled” and uneven. The presence of this defect can be attributed to the differential transverse shrinkage induced by the frequent presence of veins or casts of tension wood within this species (Washusen and Ilic 2001), and it has been shown to cause product recovery losses in sawn timber (Washusen 2011). Compression had less impact on the grade recovery of *E. nitens* veneer.

McGavin *et al.* (2014b) reported a grade scenario based on the improvement of veneer grade made possible with the implementation of effective pruning. For *E. globulus*, the simulated improvement included changes in veneer grade recovery percentage of −9% for D-grade, +11% for C-grade, and +5% for B-grade (difference between measured and simulated). A-grade remained unchanged at 0%. The simulated benefits of pruning were not supported within this study for *E. globulus*, with a negligible difference in grade recovery between the pruned and thinned sites and the two unpruned and unthinned sites. The presence of defects, including bark pockets and decay, which were mostly associated with knots, encased knots, surface roughness, and gum pockets in similar proportions across all sites, suggest that at the Deans Marsh site the pruning had not been effective in allowing clear wood to be produced. This may be due to suboptimal pruning techniques, timing and procedures, and/or may be a physiological characteristic of this species (Wardlaw and Neilson 1999; Pinkard 2002; Pinkard *et al.* 2004; O’Hara 2007; Deflorio *et al.* 2007). An additional influence may be the below average rainfall (665 mm in 2004, 709 mm in 2005, and 474 mm in 2006 recorded at the site compared with a 852 mm long-term average) the Deans Marsh site received for the three years following the last pruning. This almost certainly impacted the rate and processing of branch stub occlusion.

The same grade scenario reported by McGavin *et al.* (2014b) simulating effective pruning for *E. nitens* produced a change in grade recovery percentage of −33% for D-grade, +16% for C-grade, and +19% for B-grade grade (difference between measured and simulated). This is close to what was observed in the present study, with D-grade recoveries for both the thinned and pruned sites having between 28% and 41% less than the unthinned and unpruned site, while C-grade recoveries for the thinned and pruned sites were between 13% and 16% higher than the unthinned and unpruned Florentine site.

The thinned and pruned Strathblane site had the most favourable result and was comparable to the grade simulation, with 22.5% higher grade recovery for B-grade veneers when compared with the Florentine site. The thinned and pruned Geeveston site produced 7% higher B-grade than the Florentine site. The gains simulated by McGavin *et al.* (2014b) and measured in this study are greater than the grade quality difference reported by Blakemore *et al.* (2010) for a small study that included five pruned and five unpruned *E. nitens* trees. In this study, the changes in percentage recoveries with pruned billets compared with unpruned billets were as follows: A-grade +5.7%; B-grade +3.1%; C-grade +3.8%; D-grade +0.5%; and reject grade −13.1%. It should be noted, however, that the veneer quality from the unpruned trees was already much higher than presented in Table 5, with over 50% of the resulting veneer achieving C-grade or better. Moreover, the trees sampled by Blakemore *et al.* (2010) were bigger (mean diameter of 50.6 cm) than in this study, and the peeling and grading methods were different, making any comparison between the studies speculative.

Across all sites, the major cause for veneer being labelled reject grade was a combination of multiple defects that individually were within permissible limits of higher grades, but when combined in close proximity (*i.e.*, defect combination), prevent veneers from attaining higher grades. For the *E. globulus* sites, the high incidence of a range of...
defects, including bark and decay, encased knots, gum pockets, etc. contributed to reject recoveries of between 10.0% and 14.6%. For *E. nitens*, the Strathblane and Florentine sites had low reject recoveries (1.8% to 2.8%); however, the heavily thinned and pruned Geevoston site had 10.5% reject recovery. The defect that contributed to this variation was the high occurrence of splits in Geevoston veneers. The Geevoston billets were also observed to have severe splitting prior to peeling, which obviously carried through to the veneer. The presence of these splits is an indicator of high levels of growth stresses, most likely exacerbated by the relatively late and heavy thinning. This may have caused severe destabilisation among the remaining trees and consequently induced high levels of growth stresses. The release of these stresses has been shown to result in severe billet end splitting (Kubler 1988).

Figures 1 through 6 illustrate the distribution of assigned grades for individual grade-limiting defects for each species. In this type of diagram, each bubble represents the percentage of a given grade for a given defect. The grey scaling and diameter of the bubble are both proportional to the percentage of the total veneer surface area for each individual defect. In addition, similarly for each defect, the assigned grade is determined for each veneer from the defect(s) causing the lowest individual grade.

![Fig. 1. Distribution of Deans Marsh *Eucalyptus globulus* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.](image)

From these figures, the distribution of grade-limiting defects within C-grade and higher-grade veneer show some dissimilarities. For *E. globulus*, the most noticeable variation involves the Deans Marsh site, where insect tracks and gum veins have more impact on the reduction of veneer grade compared with the other two *E. globulus* sites at Orford and Mumbannar. This demonstrates the negative impact of pruning followed immediately by drought.

For *E. nitens*, the presence of holes impacted the Florentine site at a much lower grade compared with Strathblane and Geeveston. This is a consequence of dead branch persistence in logs from this unpruned and unthinned site.

**Fig. 2.** Distribution of Orford *Eucalyptus globulus* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

**Fig. 3.** Distribution of Mumbarrar *Eucalyptus globulus* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

Fig. 4. Distribution of Strathblane *Eucalyptus nitens* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

Fig. 5. Distribution of Geeveston *Eucalyptus nitens* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.
Fig. 6. Distribution of Florentine *Eucalyptus nitens* visually-assigned veneer grades for a range of resource-related defects. Like the grey scale, the size of the bubble is proportional to the recovered value.

**Economic Impact**

Table 7 displays the relative veneer value as a proportion of the maximum possible value for each site. The analysis acknowledges that the maximum value can only be achieved if the A-grade recovery is 100%.

**Table 7. Relative Veneer Value as a Proportion of Maximum Possible Value***

<table>
<thead>
<tr>
<th>Plantation Location</th>
<th>Species</th>
<th>Thinned and Pruned</th>
<th>Proportion of Maximum Possible Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deans Marsh</td>
<td><em>Eucalyptus globulus</em></td>
<td>Yes</td>
<td>29.0</td>
</tr>
<tr>
<td>Orford</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>30.4</td>
</tr>
<tr>
<td>Mumbannar</td>
<td><em>Eucalyptus globulus</em></td>
<td>No</td>
<td>30.3</td>
</tr>
<tr>
<td>Strathblane</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>39.9</td>
</tr>
<tr>
<td>Geeveston</td>
<td><em>Eucalyptus nitens</em></td>
<td>Yes</td>
<td>32.8</td>
</tr>
<tr>
<td>Florentine</td>
<td><em>Eucalyptus nitens</em></td>
<td>No</td>
<td>33.2</td>
</tr>
</tbody>
</table>

*A-grade recovery of 100% is used as a benchmark for the maximum percentage value.

There was minimal variation between the *E. globulus* sites. Deans Marsh veneers, which received the most intensive silvicultural treatment out of the *E. globulus* sites, demonstrated no benefit in terms of veneer grade quality and achieved a slightly lower relative value. The lower value in comparison with the other *E. globulus* sites is a direct result of the higher proportion of reject grade, which attained no value in the analysis.

More variation existed within the *E. nitens* analysis in line with the grade recovery variation. Strathblane proved to be superior, achieving 40% of the maximum possible value. This was greatly assisted by the higher proportion of B-grade by comparison, which attracts a value 1.7 times the value of D-grade. In relative veneer...
value, the Strathblane site had a 22% gain over Geeveston, which attained a similar relative veneer value to the Florentine site. While Geeveston achieved much higher proportions of C-grade and better veneers in comparison with the Florentine site, it was not enough to offset the impact of the high proportion of reject grade by comparison, which attained no value in the analysis.

CONCLUSIONS

1. This study demonstrated that plantation *E. globulus* and *E. nitens* can produce acceptable marketable product recoveries of rotary veneer; however, the graded veneer recovery was dominated by D-grade veneer across most sites. The low recovery of higher-grade veneers (C-grade and better), which are more in demand for face veneers, will make the commercial production of a standard mix of salable structural panel products challenging if relying on this resource alone.

2. Variation between the *E. nitens* sites was evident, with gross, net, and grade recoveries being different between sites that were thinned and pruned and the site that wasn’t. The best-performing site (Strathblane) achieved a recovery of C-grade and better veneers by 45%. This exceeds the minimum grade quality proportions nominated by the Engineered Wood Products Association of Australasia (30% to 40%) necessary for the commercial production of structural panel products.

3. Variation in recoveries was less evident between the thinned and pruned *E. globulus* site, as well as between the unthinned and unpruned sites. The presence of defects, including bark pockets and decay, which were mostly associated with knots, encased knots, surface roughness, and gum pockets in similar levels across all sites suggests that while pruning and thinning were conducted within the Deans Marsh site, the pruning had not been effective in allowing clear wood to be produced. This may be because of suboptimal pruning techniques, timing and procedures, physiological characteristics of this species, or drought stress resulting from the below average rainfall for the three years following the last pruning.

4. The difference in grade recovery between the thinned and pruned *E. nitens* sites and the unthinned and unpruned site was in line with the grade simulation reported by McGavin *et al.* (2014b), which describes the improvement of veneer grade by implementing effective pruning. The simulated benefits of pruning were not supported within this study for *E. globulus*, with negligible difference in grade recovery between the pruned and thinned site and the two unpruned and unthinned sites. These results indicate that the grade scenario methodology to simulate the potential grade improvement with effective pruning as proposed by McGavin *et al.* (2014b) could be a valuable tool for use in the economic modelling of silvicultural treatments, at least for *E. nitens*.

5. The veneer value analyses demonstrated minimal difference between the *E. globulus* sites, which is in line with the grade recovery. The higher proportion of reject grade veneers produced by the Deans Marsh site contributed to the slightly lower value in comparison with the other sites, despite this site receiving intensive silvicultural treatments. More variation existed within the *E. nitens* analysis. The Strathblane site proved to be superior, achieving 40% of the maximum possible value. This was
greatly assisted by the higher proportion of B-grade by comparison, which attracts a value 1.7 times the value of D-grade. Like the Strathblane site, Geeveston was also thinned and pruned; however, this site attained a similar relative veneer value to the Florentine site, which received no treatment. While Geeveston achieved much higher proportions of C-grade and better veneers in comparison with the Florentine site, it was not enough to offset the impact of the high proportion of reject grade by comparison, which attained no value in the analysis.

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The authors are grateful for the support of the Queensland Government, Department of Agriculture, Fisheries and Forestry; the Cooperative Research Centre for Forestry; the National Centre of Future Forest Industries; and the Engineered Wood Products Association of Australasia. The following companies and individuals are also acknowledged for providing the plantation resource, assistance with labour and equipment, and access to the trial sites: Forestry Tasmania, Australian Bluegum Plantations of Victoria, New Forests of Victoria, PF Olsen of Victoria, and private plantation grower David Swann of Victoria. Austral Plywoods are also acknowledged for technical support and access to commercial facilities for veneer drying.

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CHAPTER 5: Stiffness and density analysis of rotary veneer recovered from six species of Australian plantation hardwoods

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 Buuren 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). Baillères 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 dumii (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**

<table>
<thead>
<tr>
<th>Species</th>
<th>Age (years)</th>
<th>Plantation Location</th>
<th>Number of Trees</th>
<th>Average DBHOB * (cm)</th>
<th>Number of Billets</th>
<th>Number of Sampling Strips</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Corymbia citriodora subsp. variegata</em></td>
<td>10–12</td>
<td>Northern New South Wales and South-east Queensland</td>
<td>80</td>
<td>20.6 (2.5)</td>
<td>215</td>
<td>713</td>
</tr>
<tr>
<td><em>Eucalyptus cloeziana</em></td>
<td>12–15</td>
<td>South-east Queensland</td>
<td>55</td>
<td>31.9 (6.3)</td>
<td>223</td>
<td>967</td>
</tr>
<tr>
<td><em>Eucalyptus dunnii</em></td>
<td>11</td>
<td>Northern New South Wales</td>
<td>60</td>
<td>22.9 (3.5)</td>
<td>148</td>
<td>500</td>
</tr>
<tr>
<td><em>Eucalyptus pelita</em></td>
<td>13</td>
<td>North Queensland</td>
<td>38</td>
<td>28.1 (4.3)</td>
<td>130</td>
<td>1013</td>
</tr>
<tr>
<td><em>Eucalyptus nitans</em></td>
<td>20–22</td>
<td>Tasmania</td>
<td>41</td>
<td>34.0 (7.4)</td>
<td>82</td>
<td>972</td>
</tr>
<tr>
<td><em>Eucalyptus globulus</em></td>
<td>13–16</td>
<td>Victoria</td>
<td>60</td>
<td>30.6 (3.7)</td>
<td>120</td>
<td>1187</td>
</tr>
</tbody>
</table>

* 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](image-url)
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),

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

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 (inflection 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**  | **Mean**     | **Std.**    |
|                        |                  | **Number**  | **Statistic**| **Error**   |
| *Corymbia citriodora*  | Density (kg/m³)  | 713         | 795          | 2.83        | 76          |
|                        | MoE (MPa)        | 713         | 16,005       | 152         | 4053        |
|                        | Specific MoE     | 713         | 20.1         | 0.166       | 4.4         |
|                        | [(MPa)/[kg/m³]]  |             |              |             |             |
| *Eucalyptus cloeziana* | Density (kg/m³)  | 962         | 805          | 3.1         | 96          |
|                        | MoE (MPa)        | 962         | 16,177       | 134         | 4155        |
|                        | Specific MoE     | 962         | 20.0         | 0.145       | 4.5         |
|                        | [(MPa)/[kg/m³]]  |             |              |             |             |
| *Eucalyptus dunnii*    | Density (kg/m³)  | 500         | 607          | 2.94        | 66          |
|                        | MoE (MPa)        | 500         | 12,304       | 161         | 3606        |
|                        | Specific MoE     | 500         | 20.1         | 0.22        | 4.9         |
|                        | [(MPa)/[kg/m³]]  |             |              |             |             |
| *Eucalyptus pellita*   | Density (kg/m³)  | 1,013       | 748          | 2.51        | 80          |
|                        | MoE (MPa)        | 1,013       | 13,734       | 120         | 3604        |
|                        | Specific MoE     | 1,013       | 18.3         | 0.138       | 4.4         |
|                        | [(MPa)/[kg/m³]]  |             |              |             |             |
| *Eucalyptus nitens*    | Density (kg/m³)  | 972         | 608          | 2.55        | 79          |
|                        | MoE (MPa)        | 972         | 14,520       | 121         | 3766        |
|                        | Specific MoE     | 972         | 23.8         | 0.16        | 5.0         |
|                        | [(MPa)/[kg/m³]]  |             |              |             |             |
| *Eucalyptus globulus*  | Density (kg/m³)  | 1,187       | 710          | 2.96        | 102         |
|                        | MoE (MPa)        | 1,186       | 15,896       | 142         | 4904        |
|                        | Specific MoE     | 1,186       | 22.2         | 0.162       | 5.6         |
|                        | [(MPa)/[kg/m³]]  |             |              |             |             |

*Eucalyptus cloeziana* achieved the highest average density at 805 kg/m³, followed closely by *C. citriodora* with 795 kg/m³. *Eucalyptus pellita* followed with 748 kg/m³ and then *E. globulus* with 710 kg/m³. *Eucalyptus nitens*, despite being from the oldest plantations, and *E. dunnii* had similar lowest mean densities of 608 kg/m³ and 607 kg/m³, 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/m³ (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/m³), 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**

<table>
<thead>
<tr>
<th>Property (kg/m³)</th>
<th>Species</th>
<th>Kolmogorov-Smirnov*</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>Density</td>
<td><em>Corymbia citriodora</em></td>
<td>.023</td>
<td>713</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus cloeziana</em></td>
<td>.058</td>
<td>962</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus dunnii</em></td>
<td>.024</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus globulus</em></td>
<td>.038</td>
<td>1186</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus nitens</em></td>
<td>.048</td>
<td>972</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus pellita</em></td>
<td>.030</td>
<td>1013</td>
</tr>
<tr>
<td>MoE (MPa)</td>
<td><em>Corymbia citriodora</em></td>
<td>.037</td>
<td>713</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus cloeziana</em></td>
<td>.043</td>
<td>962</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus dunnii</em></td>
<td>.044</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus globulus</em></td>
<td>.049</td>
<td>1186</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus nitens</em></td>
<td>.020</td>
<td>972</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus pellita</em></td>
<td>.037</td>
<td>1013</td>
</tr>
<tr>
<td>Specific MoE</td>
<td><em>Corymbia citriodora</em></td>
<td>.028</td>
<td>713</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus cloeziana</em></td>
<td>.043</td>
<td>962</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus dunnii</em></td>
<td>.047</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus globulus</em></td>
<td>.029</td>
<td>1186</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus nitens</em></td>
<td>.027</td>
<td>972</td>
</tr>
<tr>
<td></td>
<td><em>Eucalyptus pellita</em></td>
<td>.022</td>
<td>1013</td>
</tr>
</tbody>
</table>

* This is a lower bound of the true significance.
* 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>
<thead>
<tr>
<th>Table 4. Test of Homogeneity of Variances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Levene Statistic</strong></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Density (kg/m²)</td>
</tr>
<tr>
<td>33.628</td>
</tr>
<tr>
<td>MoE (MPa)</td>
</tr>
<tr>
<td>27.473</td>
</tr>
<tr>
<td>Specific MoE</td>
</tr>
<tr>
<td>18.711</td>
</tr>
</tbody>
</table>

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 same species, but not between *E. dunnii*, *C. citriodora*, and *E. cloeziana* (Table 7).

<table>
<thead>
<tr>
<th>Table 5. Homogeneous Subsets Based on Density Following Stepwise Step-Down Comparisons using Dunn's Procedure with a Bonferroni Correction for Multiple Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
</tr>
<tr>
<td>------------------------------</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
</tr>
<tr>
<td>Corymbia citriodora</td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
</tr>
</tbody>
</table>

Homogeneous subsets are based on asymptotic significances.
The significance level is .05.
Each cell shows the sample median density (kg/m²).

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

<table>
<thead>
<tr>
<th>Species</th>
<th>Subset</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus dunnii</td>
<td></td>
<td>11,993.5</td>
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<td></td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
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<td>13,434.5</td>
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<td></td>
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<tr>
<td>Eucalyptus nitens</td>
<td></td>
<td>14,598.0</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td></td>
<td>15,416.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corymbia citriodora</td>
<td></td>
<td>15,790.0</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td></td>
<td>16,623.0</td>
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<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Species</th>
<th>Subset</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus pellita</td>
<td></td>
<td>18.314</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
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<tr>
<td>Corymbia citriodora</td>
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<td>19.975</td>
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<tr>
<td>Eucalyptus cloeziana</td>
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<td>20.357</td>
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<tr>
<td>Eucalyptus globulus</td>
<td></td>
<td>21.928</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td></td>
<td>24.046</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Species</th>
<th>Subset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>a</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td>a</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>b</td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
<td></td>
</tr>
<tr>
<td>Corymbia citriodora</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td></td>
</tr>
</tbody>
</table>

Table 9. Homogeneous Subsets Based on MoE

<table>
<thead>
<tr>
<th>Species</th>
<th>Subset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>a</td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
<td>b</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td>c</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td></td>
</tr>
<tr>
<td>Corymbia citriodora</td>
<td>d</td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td></td>
</tr>
</tbody>
</table>

Table 10. Homogeneous Subsets based on Specific MoE

<table>
<thead>
<tr>
<th>Species</th>
<th>Subset</th>
</tr>
</thead>
<tbody>
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<td>1 2 3 4</td>
</tr>
<tr>
<td>Eucalyptus pellita</td>
<td>a</td>
</tr>
<tr>
<td>Eucalyptus dunnii</td>
<td>b</td>
</tr>
<tr>
<td>Corymbia citriodora</td>
<td>b</td>
</tr>
<tr>
<td>Eucalyptus cloeziana</td>
<td>b</td>
</tr>
<tr>
<td>Eucalyptus globulus</td>
<td>c</td>
</tr>
<tr>
<td>Eucalyptus nitens</td>
<td></td>
</tr>
</tbody>
</table>

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/m³).
Table 11. Fitted Parameters for Density and MoE Across the Radius

<table>
<thead>
<tr>
<th>Parameters</th>
<th>E. nitens</th>
<th>E. globulus</th>
<th>E. pellita</th>
<th>E. dunnii</th>
<th>C. citriodora</th>
<th>E. cloeziana</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>Minimum: 552 589 587 549 707 643</td>
<td>Maximum: 634 784 758 640 833 822</td>
<td>Inflexion position: 83 73 33 59 39 50</td>
<td>Rate at inflexion: 2 3 8 2 2 6</td>
<td>R²: 0.11 0.32 0.12 0.12 0.18 0.16</td>
<td></td>
</tr>
<tr>
<td>MoE (MPa)</td>
<td>Minimum: 10655 10512 9379 7790 11090 10543</td>
<td>Maximum: 15698 18839 14328 13769 18291 17574</td>
<td>Inflexion position: 59 72 40 55 43 59</td>
<td>Rate at inflexion: 48 171 131 223 174 248</td>
<td>R²: 0.18 0.31 0.07 0.18 0.28 0.23</td>
<td></td>
</tr>
</tbody>
</table>

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

*Eucalyptus cloeziana* had a higher starting point at 643 kg/m³, while *C. citriodora* had the highest density starting point at 707 kg/m³. The maximum density values showed
more disparity, with *C. citriodora* and *E. cloeziana* producing comparable and the highest fitted values (833 and 822 kg/m³ respectively). *Eucalyptus nitens* and *E. dunnii* both produced comparable and low fitted maximum densities of around 640 kg/m³.

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. citriodora* 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. nitens’*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 (R²) 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.
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

<table>
<thead>
<tr>
<th>Parameters</th>
<th><em>E. nitens</em></th>
<th><em>E. globulus</em></th>
<th><em>E. pellita</em></th>
<th><em>E. dunnii</em></th>
<th><em>C. citriodora</em></th>
<th><em>E. cloeziana</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>562</td>
<td>587</td>
<td>723</td>
<td>511</td>
<td>727</td>
<td>578</td>
</tr>
<tr>
<td>Maximum</td>
<td>632</td>
<td>780</td>
<td>754</td>
<td>639</td>
<td>832</td>
<td>821</td>
</tr>
<tr>
<td>Inflexion position</td>
<td>7556</td>
<td>4758</td>
<td>2067</td>
<td>885</td>
<td>1543</td>
<td>1144</td>
</tr>
<tr>
<td>Rate at inflexion</td>
<td>0.010</td>
<td>0.015</td>
<td>0.005</td>
<td>0.018</td>
<td>0.021</td>
<td>0.059</td>
</tr>
<tr>
<td>R²</td>
<td>0.11</td>
<td>0.32</td>
<td>0.03</td>
<td>0.13</td>
<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>MoE (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>12037</td>
<td>10304</td>
<td>11978</td>
<td>7659</td>
<td>13643</td>
<td>10200</td>
</tr>
<tr>
<td>Maximum</td>
<td>15812</td>
<td>18732</td>
<td>14167</td>
<td>13470</td>
<td>18019</td>
<td>17502</td>
</tr>
<tr>
<td>Inflexion position</td>
<td>1226</td>
<td>5434</td>
<td>1504</td>
<td>3084</td>
<td>2112</td>
<td>3014</td>
</tr>
<tr>
<td>Rate at inflexion</td>
<td>0.13</td>
<td>0.96</td>
<td>0.29</td>
<td>11.67</td>
<td>0.84</td>
<td>2.00</td>
</tr>
<tr>
<td>R²</td>
<td>0.16</td>
<td>0.32</td>
<td>0.05</td>
<td>0.22</td>
<td>0.23</td>
<td>0.23</td>
</tr>
</tbody>
</table>

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 of 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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CHAPTER 6: Synthesis

The dissertation focused on the evaluation of rotary veneer produced by spindleless lathe veneer processing methods from Australian-grown hardwood plantations. Six commercially important plantation species were included in the study and sampled plantation areas were representative of the plantations that are available to industry for processing now and in the immediate future. The research was conducted at a scale covering the resource diversity which could be processed within an industrial facility.

Veneer processing was found to be an efficient method of conversion for fast grown hardwood plantation trees compared to other approaches such as sawing. The use of spindleless lathe veneer processing methods demonstrated many advantages compared to traditional veneer processing methods. One major advantage was the demonstration that relatively inexpensive, compact and simple equipment can be used to successfully produce usable and marketable veneer.

The study demonstrated that spindleless lathes can be used to produce attractive recoveries of rotary veneer (Chapter 2). Green veneer recoveries of around 70% and gross veneer recoveries of around 60% are in the order of two to six times what is usually achieved from processing similar resources using traditional methods. Green veneer recovery rates were independent of species and could be explained by log size and shape. Billet small-end diameter and sweep were identified as having most influence on green recovery.

The graded veneer recovery was dominated by D-grade veneer across all species (Chapter 2). 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 core veneers for the vast majority of appearance and non-appearance structural panels. If processors were relying solely on this grade of resource, the low recovery of higher grade veneers (C-grade and better) would make the commercial production of a standard mix of saleable structural panel products challenging because of the insufficient qualities of face veneer. However, the blending of plantation hardwood veneer with a small quantity of higher grade veneer may produce a suitable mix for a range of end products.

The veneers contained a range of defects that impacted the final assigned grade. The presence of gum pockets, gum veins, bark pockets and decay, encased knots, veneer roughness and splits were the most influential in limiting higher grades being achieved (Chapters 3 and 4). Various grade scenarios were found to have a positive influence on grade recovery and potential veneer value (Chapter 3). A scenario modelling the grade change that results from pruning demonstrated the potential for substantial improvements in veneer grade as knots and other associated defects were reduced. The modelling approach could be further developed to allow a range of management scenarios to be evaluated including plantation rotation age.

Further analysis which evaluated within the species grade recovery variation for logs sourced from plantations with different growing environments and different silvicultural treatments (pruning and thinning) demonstrated that higher growth rates and investments in silviculture may not always be effective in improving grade quality and value (Chapter 4). The factors influencing the lack of effectiveness was not investigated during the study however may be attributed to suboptimal pruning techniques, timing
and procedures, physiological characteristics of particular species or climate at the time of pruning. Opportunities exist to further research the effectiveness of silviculture treatments and the influence that they have on resulting veneer grade and potential value.

The study demonstrated that there are large differences in density, MoE and, specific MoE between species and the ranking of species depends on the parameter considered (Chapter 5). A wide variation of properties within species was also confirmed due to the relative enlargement of the juvenile zone over the radius as a result of fast growth and relatively short rotation length. Large gradients of properties were observed, generally evolving from low to higher values, following a sigmoid pattern. Despite these wood properties variations, the average properties recovered make the veneer suitable for the manufacture of structural products. Segregation and sorting systems would be necessary to efficiently control the use of the available veneer qualities in order to maximise the potential value in structural end-products. Opportunities exist to undertaken further research in developing optimised product construction strategies specific to end-products that maximise the utilisation of the available qualities whiles maximising the end-product qualities.

Given the various positive attributes identified for the processing method, the opportunity exists to explore an alternative to the traditional paradigm of large centralised operations through the establishment of smaller satellite rotary peeling operations. These smaller operations could be located much closer to the forest, therefore reducing log haulage distances and associated costs. Indeed, the equipment installations have the potential to be relocatable by moving to new areas of forest as
required. This approach could be particularly attractive to locations where plantation areas are widely distributed. Unseasoned or semi-dried veneers could then be transported to a main hub where veneer drying and further processing would occur. This could significantly reduce the transported volume and weight, and therefore reduce the associated costs as only recovered and usable veneer would need to be transported.

The use of spindleless veneering technology enables processing of log sizes and log qualities unable to be physically processed using alternative and more traditional methods. The ability to peel a log leaving a peeler core less than 50 mm diameter signifies that much more of the log can be recovered than by using other processing systems which target value-added outcomes. Veneer processing using spindleless methods was demonstrated as able to overcome many of the processing challenges identified as barriers for more traditional approaches when converting plantation logs (e.g. small diameter logs, growth stresses, end splits, variation in wood properties).

While the study focused on the veneer performances and qualities that were recovered by using this processing method, opportunities exist to assess the performance of the technology itself. Despite the principle of spindleless lathes have existed for many decades, their adoption within industry has been limited for various reasons including the production of unacceptable veneer thickness variation (Baldwin 1995). Rapid developments in recent years has enabled designs to progress from mechanical controls to more advanced operating and control systems that incorporate approaches such as direct servo controls to improve the lathe performance (Guo and Yang 2010). An assessment of lathe specifications, designs, control systems and resulting performances would aid in the selection of suitable equipment for any given industrial application.
In addition, processing protocols surrounding the lathe requires further investigation. Optimisation of log storage and billet pre-conditioning (i.e. temperature and method of heating) will enable improved veneer peeled qualities and allow more effective log management prior to processing. This would enable better management of log splitting during log storage and during pre-conditioning. Similarly, while veneer drying didn’t expose any difficulties during the study, opportunities exist to investigate more optimised drying conditions. Optimised parameters have the potential to lead to reduced drying time, reduced drying cost and improved veneer quality. Research in these areas would be a logical extension to the work detailed in this dissertation.

Given the spindleless lathe processing methods are capable of processing small diameter logs, opportunities of reducing final harvest age should be further investigated. Shortened rotation lengths could also reduce the effectiveness of classical silvicultural treatments as volume growth post treatment (i.e. pruning) may be too short to produce sufficient quality and/or quantity gain to offset the cost of treatment. Indeed, short rotation lengths and minimal silviculture may reduce defect size and severity (i.e. small tight knots compared with large decayed knots) to within limits more acceptable for product manufacture. Reduced rotation lengths would be expected to have a positive influence on the profitability for forest growers.

The methodology adopted during the study enabled density, MoE and specific MoE to be characterised across the billet radius and also along the veneer ribbon length (Chapter 5). The successful use of this methodology supports the findings of Wang et al. (2012) that rotary veneer can provide a very effective tool to facilitate systematic
sampling for thorough wood properties measurement. Using this method, other properties such as shrinkage, colour, moisture content and grain deviation could be more accurately determined and quantified in terms of within tree, between tree and between area variations. Given the method essentially unrolls the tree along its material growth pattern and with minimal waste, opportunities exist to further evaluate internal defects such as knots, gum veins and decay to gain a clearer understanding of the defect evolution and the tree’s reaction to specific events (e.g. pruning, thinning, disease, fire). Indeed, with the combined knowledge of log geometry, log internal structure and wood properties gained from rotary veneer, the opportunity exists to digitally reconstruct the tree structure and properties topography. Simulations could be then conducted by applying various processing methods targeting different end-products with the resulting volume and quality being modelled. From this, the most profitable processing and target end-products could be determined for any given forest resource.

The study has successfully demonstrated that the Australian plantation hardwood resources can be processed into rotary veneer using spindleless lathe methods. The resulting veneer has visual qualities and mechanical properties that are suitable for the manufacture of structural products. Further research is necessary to determine the most suitable structural products and the manufacturing protocols required to efficiently make them. Unreliable bonding performances would need to be resolved (Hopewell et al 2008, Thomas et al. 2009, Farrell et al 2011, Bailleres et al. 2013). Efficient construction strategies that optimise the use of the available veneer grade and mechanical qualities would need to be developed. Consideration should also be given to the blending of plantation hardwood veneer with veneers from other forest resources to further improve resource usage and final product qualities and performances. Any
research in this area would necessitate a detailed review of the market to enable the identification of products and market niches that better suit the qualities and performances of the plantation veneers. A thorough value chain analysis would be necessary to identify the most profitable production scenarios.
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Author/s:
McGavin, Robert Lee

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