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Properties of rotary peeled veneer and laminated veneer lumber (LVL) from New Zealand grown *Eucalyptus globoidea*

Fei Guo and Clemens Michael Altaner*

Abstract

Background: *Eucalyptus* species can be alternative plantation species to *Pinus radiata* D.Don (radiata pine) for New Zealand. One promising high value use for eucalypts is laminated veneer lumber (LVL) due to their fast growth and high stiffness. This study investigated the suitability of *Eucalyptus globoidea* Blakely for veneer and LVL production.

Methods: Twenty-six logs were recovered from nine 30-year-old *E. globoidea* trees. Growth-strain was measured using the CIRAD method for each log before they were peeled into veneers. Veneer recovery, veneer splitting and wood properties were evaluated and correlated with growth-strain. Laminated veneer lumber (LVL) panels were made from eucalypt veneers only or mixed with radiata pine veneers to investigate the bonding performance of *E. globoidea*.

Results: Veneers with no, or limited, defects can be obtained from *E. globoidea*. Veneer recovery (54.5%) correlated with growth-strain and was highly variable between logs ranging from 23.6% to 74.5%. Average splitting length in a veneer sheet was 3.01 m. There was a moderate positive association between splitting length and growth-strain ($r = 0.73$), but no significant association with wood stiffness ($r = 0.27$). Bond quality of LVL panels prepared using *E. globoidea* veneer and a phenol formaldehyde adhesive did not satisfy AS/NZ 2098.2.

Conclusion: Usable veneers for structural products could be obtained from *E. globoidea* at yields of up to 74.5%, but variation in the existing resource (which has not been genetically improved) was large. In particular, growth-strain reduced veneer recovery by splitting, largely independent of stiffness. The considerable variation in growth-strain and stiffness indicated a possibility for genetic improvement. Furthermore, a technical solution to improve bonding of *E. globoidea* veneers needs to be developed.

Keywords: Growth-strain, Bonding, Splitting, Stiffness, LVL

Background

Eucalyptus species are hardwoods and make up 26% of the global forest plantation estate (FSC 2012). Plantation eucalypt species can grow fast, reaching up to 30 cm at the base in 8 years (de Carvalho et al. 2004), and are currently mostly grown for chip wood to supply the pulp & paper industry. However, eucalypt timber is generally of higher stiffness than that of most softwood species, the main plantation resource for solid-wood processing. High stiffness is beneficial for products used in structural applications, such as in laminated veneer lumber (LVL) (Bal and Bektaş 2012). Plantation-grown eucalypts have been investigated previously for use in LVL. In general, good veneer qualities (Acevedo et al. 2012), satisfactory mechanical properties (de Carvalho et al. 2004; Palma and Ballarin 2011) and no major gluing problems were reported for eucalypt resources with air-dry densities less than 650 kg/m^3 (Hague 2013, Ozarska 1999).

A major obstacle to using eucalypts for veneers and LVL is the high level of growth-stresses present in the logs. These growth-stresses are generated by the newly formed wood cells. The exact molecular mechanism by which the cell walls generate such large stresses is unknown (Alméras and Clair 2016; Okuyama et al. 1994; Toba et al. 2013; Yang et al. 2005). However, the newly formed cells tend to contract longitudinally and expand

* Correspondence: clemens.altaner@canterbury.ac.nz
New Zealand School of Forestry, College of Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

transversely during cell wall maturation. As a consequence, the centre of the stem is under axial compression while the outside is under axial tension (Kubler 1987). These growth-stresses are released when cutting into the stem i.e. during felling, sawing or veneer peeling. The release of growth-stresses can lead to severe end-splitting following a crosscut, board distortion during sawing and breakage of veneers in the peeling process (Archer 1987; Jacobs 1945; Yang and Waugh 2001). These defects are more prominent in smaller diameter logs, i.e. a plantation resource. Splitting of veneers caused by growth-stress lowers veneer quality and reduces yield. For example, only 20% usable veneers were recovered from *E. grandis* W.Hill due to severe end-splitting (Margadant 1981). To date, no technological solution to reduce the effects of growth-stresses has been implemented successfully.

Unlike the global plantation estate, eucalypts and other hardwood species account for only 2% of the New Zealand plantation area, which is dominated by *Pinus radiata* D.Don (radiata pine) (90%) (MPI 2016). Interest in establishing commercial eucalypt plantations dates back to the late nineteenth century with the introduction and testing of many eucalypt species around that time (Barr 1996; McWhannell 1960; Miller et al. 1992; Miller et al. 2000; Shelbourne et al. 2002; Simmonds 1927). Their work identified various *Eucalyptus* species that suit New Zealand conditions. However, today *E. nitens* (H.Deane & Maiden) Maiden is the only *Eucalyptus* species that is currently grown commercially on a large scale. There are more than 10,000 ha *E. nitens* in Southland and Otago (in the southern South Island), but the species suffers from fungal and insect attack in the warmer North Island (McKenzie et al. 2003; Miller et al. 1992). Some small commercial plantings of *E. fastigata* H. Deane & Maiden and a small amount of *E. regnans* F.Muell. can also be found (Miller et al. 2000). The development of these three species is supported by breeding programmes: *E. nitens* (Telfer et al. 2015); *E. fastigata* (Kennedy et al. 2011); and *E. regnans* (Suontama et al. 2015). *Eucalyptus nitens* is currently grown for chip wood export for the pulp industry. Generally, it is possible to manufacture quality LVL from 15-year old *E. nitens*, which was reported to have an average MoE of 14.3 GPa and achieving F17 grade according to AS/NZS 2269 (2012) (Gaunt et al. 2003). This compares favourably to the majority of radiata pine LVL products manufactured in New Zealand, the MoE of which range between 8 and 13 GPa, and which relies on using the better part of the radiata pine resource. Apart from growth-stress, *E. nitens* has been reported to suffer from collapse and internal checking during drying (Lausberg et al. 1995; McKenzie et al. 2003; McKinley et al. 2002).

None of the currently commercially grown eucalypts produce naturally ground-durable and coloured timber even though the value of such a resource was identified many years ago by early eucalypt enthusiasts (McWhannell 1960; Simmonds 1927). Interest in growing these eucalypt species to produce high-value speciality timbers continued in the forestry sector but smaller growers favoured different species so no critical mass has been achieved to date. Furthermore, a successful plantation industry needs to be supported by a breeding programme (Miller et al. 2000). Tree-breeding programmes require a wide genetic basis and are costly, highlighting the need to focus resources on a few species.

Three major research initiatives involving durable eucalypts in New Zealand have been initiated in the last two decades. The Forest Research Institute (Scion) and the New Zealand Forestry Association undertook a series of trials on eucalypts with stringy bark. However, these were either discontinued due to a lack of funding or have a narrow genetic base (van Ballekom and Millen 2017). The New Zealand Dryland Forests Initiative (NZDFI) has been working since 2008 to establish a eucalypt forest industry producing naturally durable timber based on a large scale-breeding programme of three species *E. bosistoana* F.Muell., *E. quadrangulata* H. Deane & Maiden and *E. globoidea* (Millen 2009). This breeding programme took a range of wood-quality traits into account (including low growth-stress). While primarily chosen for the natural durability of their heartwood, these species also produce wood of high stiffness - up to 20 GPa (Bootle 2005). Demand for engineered timber products with exceptional stiffness has been generated by the emergence of high-rise timber buildings (Van de Kuilen et al. 2011). These species also have naturally durable heartwood so it may be possible to produce preservative-free durable LVL (McKenzie 1993; Page and Singh 2014). Some information on the wood properties of *E. bosistoana*, *E. quadrangulata* and *E. globoidea* is available from old-growth resources in Australia (Bootle 2005), but only young plantation-grown *E. globoidea* has been studied previously in New Zealand. *Eucalyptus globoidea* has been reported to be well suited for plantation forestry with good tree health, growth and adaptability combined with favourable timber properties of good stiffness and natural durability (Barr 1996; Haslett 1990; Millner 2006). Additionally, it is easy to dry and has relatively low growth-stress levels (Jones et al. 2010; Poynton 1979). No information on peeling parameters, veneer drying or bonding has been reported for this species, however.

Eucalyptus globoidea was selected for the present study to evaluate its suitability for veneer and LVL production considering the fact that sufficiently large trees could be sourced from a farm-forestry operation. To the best of our knowledge, no sufficiently large *E. bosistoana* or *E. quadrangulata* trees are available in New Zealand for processing research. Growth-strain of logs was measured and then peeled into veneers. Green veneer recovery and peeling quality were evaluated and relationships between these attributes and both growth-strain and dynamic modulus of elasticity (MoE) were investigated. Physical properties including density, shrinkage and moisture content of dried veneer were also monitored. *E. globoidea* veneers were used to manufacture pure eucalypts LVL and mixed LVL with radiata pine veneers to investigate the bonding performances.

Methods

Nine *E. globoidea* trees with straight form were randomly chosen and felled from a 30-year-old stand in the lower North Island (latitude 40° 11′ 12" S, longitude 175° 20' 35" E, elevation 60 m) in May 2016. The stems were manually debarked immediately after felling. From these stems, 26 suitable logs for peeling of 2.7 m length were recovered. The small end (SED) and large end diameters (LED) were measured for each log in order to calculate log volume.

Growth-strain measurement

For each log, the amount of growth-strain was determined with the CIRAD method (Gerard et al. 1995). The growth-strain is variable on the surface of a stem (Gerard et al. 1995). Therefore, growth-strain was measured on four positions at ~1.35 m spaced by ~90^0 around the circumference of each 2.7 m log. The four assessments for each log were averaged. Measuring points were chosen in straight-grained areas in close proximity to the above described positions in order to avoid knots. It was calculated from the measured change in distance between the pins according to Eq. (1).

$\alpha = -\phi\ \delta$ (1).

where α is the strain in microstrain; δ is the measured displacement in μm and ϕ is a constant dependent on tree species. The published value for eucalypt of $\phi = 11.6$ was used (Fournier et al. 1994).

Rotary peeling and veneer evaluation

The trees were transported to Nelson Pine Industries Ltd. (NPI), Richmond, NZ for processing. All logs were heated at 85 °C for 24 h in a water bath before peeling 8 days after felling. 23 of the 26 logs were peeled to a core diameter of 82 mm using a spindled lathe (Raute, Finland) with three-stage chucks. The remaining three logs fell off the lathe with a larger peeler core (133 to 162 mm in diameter) due to severe end-splitting. Veneers with a thickness of 3.74 mm were produced from all 26 logs. During the peeling process, the recovery and volumes of different types of waste (core, round-up, spur, clipper defects) were recorded for each log. After clipping, 296 veneer sheets were obtained. Recovery was defined as the ratio of the obtained veneer volume to log volume. Veneer volume was calculated based on the number of sheets and the thickness and dimensions of sheets. For comparison, NPI provided the average recovery data of more than 46,000 radiata pine logs (2.7 m long) collected previously from the production line. The radiata pine logs used in this study were sourced from plantations and woodlots in Nelson and Marlborough. Veneer splitting was the major defect with few knots or other defects found so the aggregate defect rule according to AS/NZS 2269.0 (2012) was not applied. The green veneer sheets were visually graded to four classes (face, core, composer, waste) according to their splitting severity by the technical manager in NPI. Only face and core grades were considered to be usable veneer.

From the dryer line with the Metriguard 2655 DFX instrument (USA), ultrasonic propagation velocity and width data were made available for each veneer sheet. The individual veneer sheets could be tracked back to the individual logs. With the clipping width known, the width data were used to calculate the tangential shrinkage. The number of splits in each veneer was counted from the Novascan grader (Grenzebach, Germany) images. ImageJ software (National Institute of Health, USA) was used to analyse the splitting lengths.

After drying, a strip approximately 200-300 mm wide was taken from a sheet near the start and the end of each veneer mat. The dimension and weight of this strip were measured to obtain dried density. These test pieces were then dried further in an oven at 103 °C until constant weight to obtain the moisture content.

The dynamic modulus of elasticity (MoE) was calculated from ultrasound acoustic propagation velocity and wood density data according to Eq. (2).

$E = V^2\rho$ (2).

Where V is the ultrasonic velocity, E is the dynamic MoE and ρ is the density. Static MoE for the population of sheets was estimated by multiplying the dynamic

Table 1 Green veneer recovery and amount of waste of *E. globoidea* compared to *P. radiata* data

	Green veneer recovery (%)	Amount of waste			
		Round-up (%)	Spur (%)	Core (%)	Clipper defects (%)
E. globoidea	54.5	4.6	2.5	12.0	20.0
P. radiata	69.8	11.2	2.7	6.0	8.3

Table 2 Summary of veneer recovery and splitting

	Recovery (%)	Useable veneer (%)	Growth-strain (με)	Splitting length (m)	Split counts
Mean	54.5	33.4	839.4	3.01	8.63
SD	14.2	23.7	181.7	2.57	5.11
Min	23.6	0.0	553.9	0.15	1.14
Max	74.5	74.5	1136.8	8.66	16.86

SD, Min and Max represent standard deviation, the minimum and maximum values respectively

MoE with a factor of 0.868. The factor was empirically determined by laminating test panels of *Eucalyptus globodiea* veneers with known dynamic MoE and conducting static 4-point bending tests in the edgewise direction.

Bonding quality of eucalyptus veneer

Ten laboratory-scale 10-ply LVL panels were manufactured. Six panels were made of eucalypt veneer only, choosing veneer sheets of defined MoE grades based on their dynamic MoE values. One panel each was made from 12, 14, or 17.5 GPa sheets and three panels were made from 16 GPa sheets. Each LVL panel contained veneer from one or two logs only. Another four panels were made of five radiata pine and five eucalypt veneer plies. A range of eucalypt grades were used in these panels. The first (14 GPa), third (17 GPa), sixth (14 GPa), eighth (12 GPa) and tenth layers (12 GPa) were eucalypt veneers and the rest were radiata pine. Two panels were made from each of G2 and G4 radiata-pine grades. A typical phenolic formaldehyde adhesive manufactured by Aica NZ Limited was used at a rate of 180 g/m^2. Panels were hot-pressed at 160 °C with a pressure of 1.2 MPa.

The quality of the glueline was assessed according to AS/NZS 2098.2 (2012), which measures the percentage of area covered by wood after two veneers have been split apart. According to AS/NZS 2269.0 (2012), bonding between the plies in LVL shall be a Type A bond. This specification requires a phenolic adhesive complying with AS/NZS 2754.1 (2016) and also a bond quality of any single glueline not less than 2 and an average of all gluelines not less than 5 when tested according to AS/NZS 2098.2 (2012). Both a steam and a vacuum pressure method were used to assess glueline quality (AS/NZS 2098.2 2012).

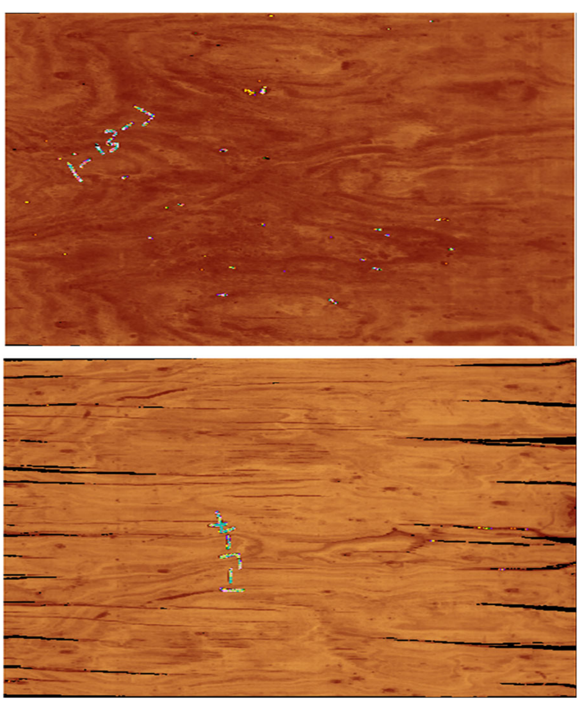

Fig. 1 Face grade veneer with no splitting (top) and composer grade veneer with severe splitting (bottom)

Results and discussion

Rotary peeling and veneer recovery

For the 26 logs of 2.7 m tested, the small end diameter averaged 34.4 cm with a standard deviation of 4.3 cm while the large end diameter averaged 38.9 cm with a standard deviation of 6.3 cm. The average diameter of the *E. globoidea* logs (36.3 cm) was comparable to the radiata pine logs (34.9 cm) used in the plant for LVL production. In a preliminary test, an additional *E. globoidea* log was peeled cold. This was unsuccessful and, therefore, preheating to soften the wood was deemed necessary.

The average veneer recovery for the 26 *E. globoidea* logs (54.5%) was lower than for radiata pine logs (69.8%)

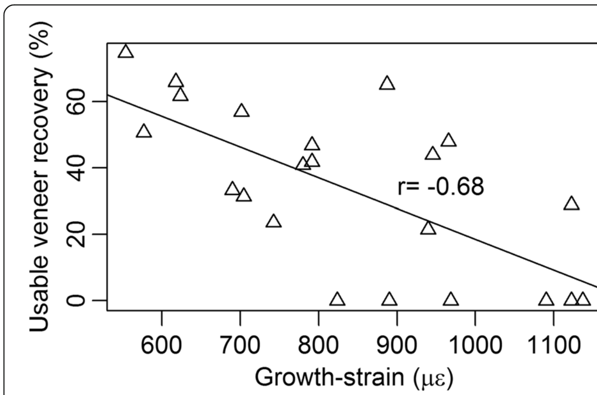

Fig. 2 Dependence of usable veneer conversions on growth-strain of the individual *E. globoidea* logs

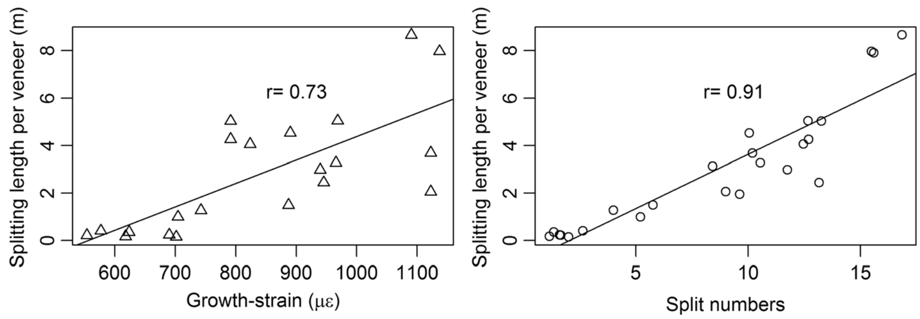

Fig. 3 Association between splitting length and growth-strain (left) as well as number of splits (right)

but the best *E. globoidea* log had a recovery of 74.5% (Tables 1 and 2). This result was mainly due to a 6% higher loss in the peeler core caused by severe splits in the supplied *E. globoidea* logs and an 11.7% greater clipper loss caused by end-splitting of the veneers compared with the radiata pine logs. However, the amount of round-up waste was lower for the eucalypt logs than the radiata pine logs, which indicated a better log form for *E. globoidea*. Veneer recovery from individual logs was highly variable ranging from 23.6% to 74.5% (Table 2). A previous peeling study with *E. nitens* reported an overall recovery of 59% (McKenzie et al. 2003). However, part-sheets were included in that study while only full sheets were calculated in the present study.

A spindled lathe was used to peel the logs in the current study but spindleless lathes are extensively used in China. They are suitable for rotary peeling smaller diameter logs from young and fast-grown hardwood plantations (McGavin 2016). Spindleless lathes achieve higher yields because they can peel logs to smaller peeler core diameters compared to spindled lathes currently used for radiata pine. Moreover, spindleless lathes can control splits by pressing the splits together during peeling. Therefore, using this type of lathe may generate higher recovery and quality of veneer sheets.

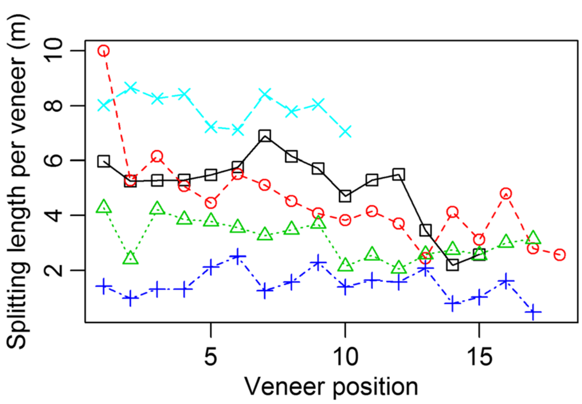

Fig. 4 Splitting length for veneers obtained from the centre to the outside of five individual logs

Growth-strain and veneer splitting

High quality veneers can be obtained from *E. globoidea* although splitting significantly degraded the visual appearance of many veneers (55% of the veneers had splitting lengths longer than 2 m). Veneers with no and severe splitting are shown in Fig. 1.

The average recovery of useable veneer (face and core grades) from *E. globoidea* was 33.4%. Severe splitting caused by growth-stress contributed to the low recovery. The average growth-strain was 839.4 με measured by the CIRAD method. The log with the lowest growth-strain had approximately half the growth-strain compared with that with the highest. Usable veneer recovery was negatively associated with growth-strain (Fig. 2). The average useable veneer recovery for the logs in the bottom quartile (growth-strain >965.7 με) was 5.8%, while that for the top quartile (growth-strain <701.8 με) was 57.2%.

The mean splitting length per veneer for individual logs ranged from 0.15 m to 8.66 m. For a veneer 2.65 m in length and 1.26 m in width, the average total splitting length was 3.01 m. This suggested splitting was limiting veneer quality.

The splitting length was measured after the veneers were dried. Drying was likely to exaggerate the splitting lengths but was assumed to affect all veneers equally in this study. In addition, rough handling and peeling settings can also contribute to the splitting of veneers. It was assumed that all veneers were equally affected in these ways and the differences among them were mainly caused by growth-stress.

A positive correlation ($r = 0.73$) was observed between splitting lengths in veneers and growth-strain of corresponding logs (Fig. 3). In this study, average splitting length was low when growth-strain was less than ~800 με (CIRAD). Longitudinal growth-strain was reported to be positively related to end-splitting of *E. nitens* and *E. globulus* logs (Valencia et al. 2011; Yang and Pongracic 2004). The number of splits in a veneer sheet is another measure to evaluate veneer spitting. A strong linear relationship ($r = 0.91$) was obtained between splitting length and split numbers (Fig. 3). Considering that the measurement of

Table 3 Physical and mechanical properties of dried *E. globoidea* veneers

	Dried density (kg/m^3)	Moisture content (%)	Shrinkage (%)	Velocity (km/s)	Dynamic MoE (GPa)
Mean	688.13	7.31	9.85	4.657	15.14
SD	68.55	1.09	0.77	0.240	2.05
Min	557.41	5.51	8.46	4.322	11.04
Max	824.00	9.32	11.31	5.097	19.51

the number of splits is less time consuming than quantifying splitting length, it might be a better option for future studies.

This result indicated that higher veneer recovery and quality would be possible if growth-stresses were reduced. Methods to control the growth-stress and minimise splitting are difficult to perform, have not been successful in industrial applications and incur ongoing costs (Archer 1987; Malan 1995; Yang and Waugh 2001). Growth-stresses are heritable and selecting trees with low growth-stress in a breeding programme can potentially solve this problem for a future resource such as *E. globoidea* (Davies et al. 2017; Malan 1995). For existing eucalypt plantations grown for the lower-value wood chips, such as *E. nitens*, segregation would be an option. However, current methods of measuring growth-stress are time consuming and cumbersome, making this approach impractical (Yang and Waugh 2001). Rapid and non-destructive segregation methods need to be developed. For example, Yang et al. (2006) measured growth-strain of 10-year-old *E. globulus* and found correlations with cellulose crystallite width measured using a SilviScan-2 instrument.

The relationship between splitting length and radial position for five logs is shown in Fig. 4. The splitting length of the veneer sheets tended to increase towards the centre of the stem (position 0). The decreasing circumference with decreasing radius results in shorter tangential distances between the radial end-splits of the logs. Furthermore, the increasing curvature with decreasing radius can facilitate splitting. However, the variation between the stems was much bigger than the radial effect, with the veneer splitting independent of radius for the worst and the best logs.

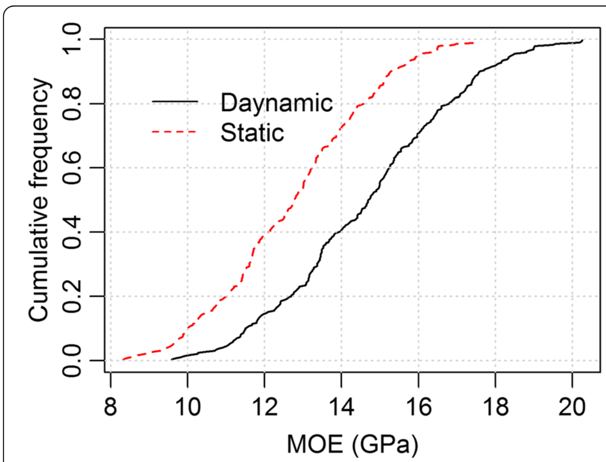

Fig. 5 Cumulative distribution of dynamic and static MoE of veneer sheets

It is worth noting that the log preheating and peeling settings in this study were optimised for radiata pine. Acevedo et al. (2012) reported that better quality veneers were obtained from *E. nitens* by adjusting nose bar pressure and peeling knife angle.

Physical and mechanical properties of veneer

After drying, the average dry density was 668 kg/m^3 and the average moisture content was 7.3% (Table 3). No excessively high or low moisture contents were found, which indicated homogeneous drying of the *E. globoidea* veneers.

The average shrinkage of the *E. globoidea* veneers was 9.9% tangentially and varied between 8.5 and 11.3%. Most veneers were heartwood as the sapwood in *E. globoidea* is very narrow. For comparison, typical tangential shrinkage values for radiata pine veneers are 6.4% for sapwood and 4.4% for heartwood. Higher shrinkage will result in greater volume loss. It should be noted that, within species, heartwood typically displays lower shrinkage than sapwood.

The average dynamic MoE calculated for the *E. globoidea* veneer sheets from Metriguard acoustic velocity and interpolated lab density was 14.67 GPa ranging from 9.59 to 20.26 GPa (Fig. 5). The equivalent static MoE was estimated to be 12.73 GPa based on the empirical conversion equation. Common LVL products manufactured from radiata pine range from 8 to 11 GPa. Jones et al. (2010) investigated 25-year-old *E. globoidea* for high-quality solid wood production. Boards from the butt logs were reported to have an average density of 655 kg/m^3, dynamic MoE of 13 GPa and static MoE of 12 GPa. According to Haslett (1990), the timber of *E. globoidea* (over 25 years old) in New Zealand has an MoE of 14.6 GPa at a moisture content of 12%.

High stiffness wood tended to have higher growth-strain (Fig. 6). This is an unfavourable association as stiff wood with low growth-strain is desirable. However, the association between MoE and growth-strain was moderate ($r = 0.65$) implying the existence of stiff logs which are low in growth-strain. Several logs produced veneers with MoEs above 15 GPa and growth-strain levels below

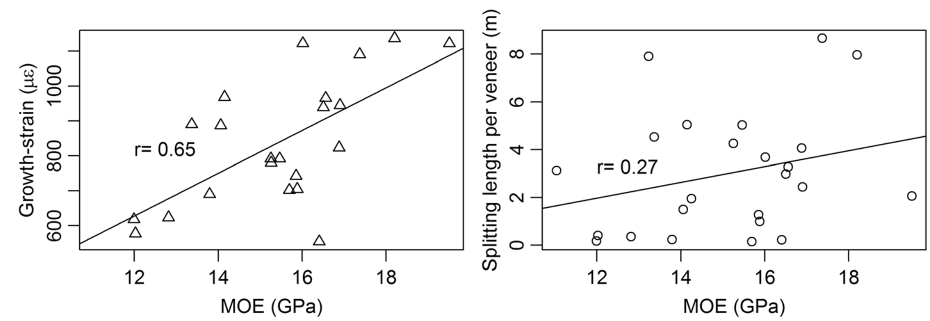

Fig. 6 Association between MoE and growth-strain (left) as well as veneer splitting (right)

800 με. More importantly no association ($r = 0.27$) was found between veneer splitting and stiffness, which demonstrated that peeling quality needs to be improved through reducing growth-stress rather than through MoE. The stiffest logs yielded veneers with an MoE of up to 19.5 GPa, but these did not necessarily have a severe splitting problem. Therefore, it seems possible to obtain a stiff eucalypt resource that yields high-quality veneers.

A weak positive association ($R^2 = 0.26$) between CIRAD longitudinal displacement and MoE has been found previously in *E. globulus* (Yang et al. 2006). With the increase of longitudinal displacement, microfibril angle tended to decline while density increased. Similar associations between growth-strain and wood properties have been reported for wood from *Populus deltoides* Bartr (Fang et al. 2008). However, no statistically significant associations were found between growth-stain and dynamic MoE or density for *E. nitens* (Chauhan and Walker 2004).

The average distribution of MoEs for the veneers obtained from the nine trees assessed is shown in Fig. 7. As for veneer splitting, the variance in MoE among trees was large with the average stiffness ranging from 12.1 GPa to 18.0 GPa. Analysis of variance found significant differences ($P < 0.001$) in MoE values of veneers from different trees.

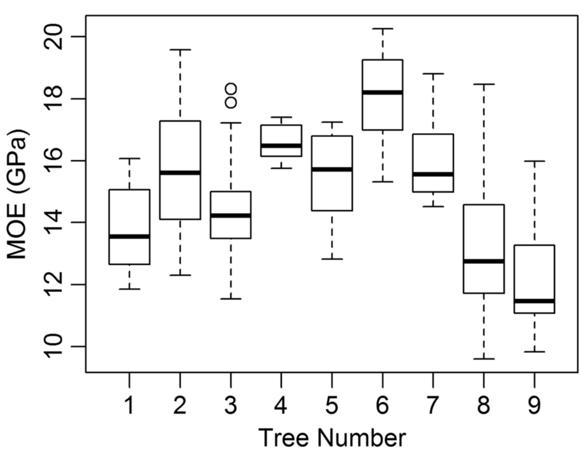

Fig. 7 Box-and-whisker plots of veneer MoE from nine trees. Dotted lines show minimum and maximum values; the thick black line shows the median; the box represents the upper and lower quartiles and outliers are marked using open circles

It has to be noted that the tested *E. globoidea* was genetically unimproved material of unknown provenance. Wood properties like growth-stress and MoE are under genetic control (Davies et al. 2017). Murphy et al. (2005) reported a heritability of 0.3 to 0.5 for growth-strain in *Eucalyptus dunnii* Maiden and indicated tree breeding can be an effective method to reduce growth-stress. Considerable variation among trees was observed, indicating a potential for genetic improvement. The relatively high acoustic velocity of eucalypts in the corewood could allow peeling veneers to a smaller peeler core with spindleless lathes, improving yields and allowing the use of a small diameter younger resource.

Bonding quality

The bond test revealed poor bonding of the plies. None of the panels made with *E. globoidea* alone passed the specifications for structural LVL (Table 4). Density seemed to exaggerate the bonding difficulty for the 100% *E. globoidea* LVL. *Eucalyptus globoidea* panels with densities higher than 800 kg/m^3 had average bonding qualities lower than 3. Alternating *E. globoidea* and *P. radiata* veneers improved bond quality, and all samples

Table 4 Bond tests of six LVL panels made from *E. globoidea* veneers (listed in order of increasing density)

Grade (GPa)	Density (g/cm^3)	Steam test			Immersion test		
		EE_{min}	EE_{max}	EE_{mean}	EE_{min}	EE_{max}	EE_{mean}
12	640.51	1	9	5	1	5	2
16	696.92	3	8	6	4	9	6
16	702.52	1	9	6	3	8	7
16	806.83	0	5	1	0	3	2
14	809.22	0	3	2	2	3	2
17.5	860.05	1	4	2	0	7	3

EE represents bond quality values between *E. globoidea* veneers (0 no bond – 10 excellent bond). The minimum, maximum and mean values are shown

Table 5 Bond tests of four LVL panels made from a mixture of *E. globoidea* and *P. radiata* veneers

Sample	Radiata pine grade	Steam test				Immersion test			
		ER_{min}	ER_{max}	RR	Mean	ER_{min}	ER_{max}	RR	Mean
1	G4	4	9	9	7	1	9	9	7
2	G4	3	7	10	5	0	9	8	6
3	G2	2	9	9	7	3	9	9	6
4	G2	2	9	9	6	1	8	9	6

G4 and G2 are radiata pine veneer grades; 12, 14 and 17.5 GPa grade eucalypt veneers were used in each sample. ER represents the gluelines between eucalypts and radiata pine veneers and RR stands for the glueline between two radiata pine veneers. Mean is the average value of all 9 gluelines

passed the steam test, but only one sample passed the immersion test. The glueline between radiata pine plies was excellent (Table 5).

Eucalypts have a higher density and extractive content than radiata pine, and both these factors can make gluing difficult. In Australia, difficulty in bonding veneers from dense eucalypts (air-dry density above 700 kg/cm^3) are known and some special adhesive formulations have been developed for these species (Carrick and Mathieu 2005; Ozarska 1999). It is commonly stated that low and medium density (below 650 kg/cm^3) eucalypts glue well but young *E. nitens* was found to have bonding issues however (de Carvalho et al. 2004, Farrell et al. 2011, Hague 2013). Plywood products made from various *Eucalyptus* species have been reported in China, Malaysia, Uruguay and Brazil indicating that satisfactory bonding can be achieved for many *Eucalyptus* species (de Carvalho et al. 2004; Hague 2013; Turnbull 2007; Yu et al. 2006). Therefore, it seems probable that a technical solution for gluing *E. globoidea* can be found.

Conclusions

1) Veneer recovery ranged from 23.6% to 74.5% among 26 *E. globoidea* logs. Larger peeler core and higher clipper losses occurred compared to radiata pine.
2) High-quality veneers could be obtained from *E. globoidea*. Low growth-strain logs produced more usable veneers. Splitting degraded veneer quality.
3) Splitting length in veneers was correlated to growth-strain of the corresponding logs. Split number was strongly associated with splitting length and can be used to evaluate veneer splitting severity. Veneers from inner wood tended to a have longer splitting lengths; however differences among logs were more pronounced.
4) Moisture contents of dried veneers indicated good drying of *E. globoidea*. The average tangential shrinkage was 9.9% and the volume loss was higher than for radiata pine. Larger shrinkage is a common feature of high-density timbers.
5) The average dynamic MoE was 14.67 GPa ranging from 9.59 to 20.26 GPa. No association was found between splitting length and stiffness. It should be possible to find stiff logs, however, which would yield satisfactory veneers. The considerable variation in stiffness observed here indicated a potential for genetic improvement.
6) The lack of association between stiffness and splitting length suggested that quick acoustic measurements for segregating eucalypt logs suitable peeling are unlikely to be successful.
7) Bond performance of *E. globoidea* LVL was poor and did not meet the New Zealand standard. Alternating *E. globoidea* and *P. radiata* veneers improved bond quality, but bonding of *E. globoidea* veneers still needs to be addressed.

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Authors' contributions
FG carried out the field work, growth-strain measurement, veneer peeling, data analysis and prepared the manuscript. CMA designed and organised the study contributed to data analysis and manuscript preparation. Both authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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