Machinability of 28-year old plantation-grown Eucalyptus globoidea timber

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Abstract

Eucalyptus globoidea is an emerging plantation species in New Zealand. Its naturally durable heartwood has potential to be used for solid wood outdoor products such as garden furniture, playground equipment, or decking. Good machinability of a timber is essential for solid wood processing but was unknown for *E. globoidea*.

This study showed that *E. globoidea* heartwood machined equally well or better than *Pinus radiata* in planing, boring, mortising, grooving, edging, and turning. Sanding the higher density *E. globoidea* (air-dry density 723 kg/m^3) was more difficult than the lower density *P. radiata* (air-dry density 461 kg/m^3) but possible at lower sanding depth. Within species, density was not a relevant factor of machining grades. Defect types determining the machine scores were identified so processing strategies for improved outcomes could be devised, for example avoiding exit points for grooving and boring.

The results will give forest growers confidence in investing in *E. globoidea* plantations as no new processing machinery is needed for the well-established *P. radiata* wood processing industry to work with this timber.

1 Introduction

High-value markets for durable timbers are well established globally but supply of these timbers is unsustainable being mainly from often illegally logged natural stands of tropical species (Nellemann 2012). Greater protection and law enforcement to restrict logging of these forests will reduce future supply to international markets (Polo Villanueva et al. 2023). For example, West Australia's jarrah (*Eucalyptus marginata*) timber industry will close in 2024.

The New Zealand Drylands Forest Initiative (NZDFI) aims to develop a sustainable eucalypt resource that supplies ground durable timber to the agricultural sectors (Millen et al. 2020). This resource will supplement New Zealand's timber supply which is currently almost exclusively based on locally grown *Pinus radiata*. *E. globoidea* has been identified as a species featuring ground-durable heartwood (AS5604) which can be grown sustainably in New Zealand's climate. The first genetically improved *E. globoidea* became available for sale in 2021.

E. globoidea timber is not only ground-durable but the higher density timber also features excellent mechanical properties (Bootle 2005; Poynton 1979), opening outdoor joinery and structural engineered wood products markets (Guo and Altaner 2018; Jones et al. 2010). Machinability of a timber, the ease of obtaining a smooth surface, is an important characteristic for solid wood processing. The American Society for Testing and Materials (ASTM) has developed a standard to quantify the machinability of timber (ASTM D1666-17). Tests are designed to reflect the variability of the surface finish for specific machining processes, which is visually graded. Machinability of some higher density eucalypts has been reported (Belleville et al. 2016) but shown to be species dependent. The machinability of *E. globoidea* is unknown.

The research objective was to assess the machinability characteristics of *E. globoidea* wood. To account for the inherently qualitative data of such assessments, the results were compared against *P. radiata*, a timber with known good machinability. Further, the locations of machining defects were noted, allowing the recommendation of improvements to the machining processes. The results will ensure market access of *E. globoidea* timber into solid wood products such as outdoor furniture, playgrounds, flooring, and decking and consequently give growers of *E. globoidea* plantations confidence in their investments.

2 Materials And Methods

2.1 Material

Eucalyptus globoidea boards originated from 31 trees felled at age 28-years old on Banks Peninsula (43°47'32.0"S; 172°50'20.8"E), New Zealand as part of a taper and volume study (Boczniewicz et al. 2022). Logs were then live sawn into 30 mm thick boards using a mobile horizontal band saw and subsequently ripped into 110 mm wide heartwood boards without pith. The boards were air-dried indoors for three years. The least defective, and most approximately flat-sawn boards were selected from the available material. Deviating from ASTM D1666-17, specimens with live knots not larger than 15 mm in width were included due to material constraint. As a control, thirteen flat-sawn, kiln-dried, rough-sawn, clears grade *Pinus radiata* boards (5,200 mm x 150 mm x 25 mm) were purchased locally.

From the rough sawn board samples for planing and sanding; grooving, edging, boring, and mortising; and turning; as well as density and moisture content determination were prepared according to ASTM D1666-17 and equilibrated to ~ 12% MC in a climate-controlled room at 65% relative humidity and 20°C.

2.2 Grading

The ASTM D1666-17 standard distinguishes five visually assigned grades for each machined surface. To ensure consistency only one person graded all samples. The grades were interpreted as follows:

Grade 1: defect-free pieces, where no fixing (sanding) would be required to finish the product to a high standard.

Grade 2: defects which could be remediated by light sanding.

Grade 3: remediation would require significant sanding or chiselling, resulting in slightly rounded edges or altered dimensions.

Grade 4: as Grade 3, except remediation will result in deep-rounded edges or visibly altered dimensions.

Grade 5: no remediation of the defect possible to achieve a high-quality surface finish.

Machining defects associated with knots were excluded from the surface quality analysis, in particularly for sanding and planing as wood near knots is at higher risk of torn grain and fuzzy grain (Öhman et al. 2016). The worst defect determined the grade of a piece. The machine score for a tool was defined as the percentage of the combined Grade 1 and 2 or Grades 1–3 as defined in (ASTM D1666-17).

2.3 Planing

Equilibrised boards were planed in random order regardless of species to remove the effect of tool wear with an SCM S630 thicknesser operated at 4500 RPM (revolutions per minute) with two new high-speed steel knives installed at a cutting angle of 30°. The feeding speed was 11.25 m/min, resulting in 0.8 cuts/mm. Samples were planed in two passes, with a first pass taking off 1 mm to remove artefacts of previous machining and a second pass taking off a further 1.6 mm of the same face. The surface quality was measured after the second pass.

2.4 Sanding

After planing, the samples were sanded using a Hafco Woodmaster DS-25 Dual Drum Sander fitted with 80-grit and 120-grit aluminium oxide paper. The feed speed was 6.1 m/min and 1.2 mm was sanded off one face for assessment. Each species was machined independently on fresh sandpaper.

2.5 Boring

A Dyco 12 mm bench drill press was used in conjunction with a 25 mm Bosch Forstner drill bit featuring a high-speed steel cutting edge to assess boring. The targeted feed speed was 0.5 m/min. The drill was run at 1200 RPM, deviating from the standard-specified 3600 RPM, as the samples burned at the higher speed. All samples were randomised. Two holes were bored into each sample and the order was reversed in the second run to remove the effect of tool wear.

For all boreholes three data points were graded independently: entry, the edge where the tool entered the wood; hole, the plane inside the borehole; and exit, the edge where the tool exited the wood. The grade of a data point on a board was the worst grade of the two holes per board.

2.6 Shaping

An Ascent Pro CNC machine was used with three router bits featuring high-speed steel cutting edges: a 6.4 mm straight bit, a 10 mm rebating bit, and an 8 mm rounding bit. The CNC machine was run with a feed speed of 4240 mm/min at 10,000 RPM. The samples were machined in random order to reduce to effect of tool wear. First, a J-shaped groove running parallel and perpendicular to the grain was cut with the 6.4 mm straight bit, followed by a rebate along the edge of the specimen, first parallel, then perpendicular, using the 10 mm rebating bit. Finally, the lower step of the rebate was rounded with the 8 mm rounding bit.

Four data points were graded for each groove: Side-grain inside the groove; the corner inside the groove; the end-grain inside the groove; and the edge where the tool exited the sample. Three data points were graded for each edge: the side-grain surface, the corner, and the end-grain surface.

2.7 Mortising

A Luxcut TM-3VSL turret mill was used in conjunction with a 13 mm custom-made high-speed cutting steel mortising chisel and a single spiral auger centre. The targeted feed speed was 0.23 m/min. Holes were mortised at 1200 RPM as the machine could not perform this task safely at the (ASTM D1666-17) specified 3600 RPM. The samples mortised in a randomised order and the two mortised holes per sample were machined in reversed order to minimise the effect of tool wear.

Four data points that were graded for each mortise hole independently: entry, the edge where the tool entered the wood; side-grain, the side-grain plane inside the borehole; end-grain, the end-grain plane inside the borehole; and exit: the edge where the tool exited the wood. The grade of a data point on a board was the worst grade of the two holes per board.

2.8 Turning

A Luxcut Z330X1000 lathe was used for turning in conjunction with a custom-made knife profiled as specified in (ASTM D1666-17) featuring a high-speed steel cutting edge. The targeted feed speed was 0.02 m/min. The lathe was run at 2000 RPM. Samples were randomised to reduce the effect of tool wear.

Four data points were graded independently per sample, at the angled, flat, concave, and convex part.

2.9 Data analysis

Regression modelling and t-tests were performed with R (R Core Team 2022).

3 Results And Discussion

Air-dry densities were significantly higher in *E. globoidea* than in *P. radiata* (Table 1). The mean air-dry density for *E. globoidea* heartwood boards cut from 28-year-old trees was 723.3 kg/m^3 with a CV of 9%. This was lower than the reported air-dry density for Australian old-growth trees (820–900 kg/m^3) (Bootle 2005) but consistent with the reported basic-density of ~ 540 kg/m^3 for 25-year-old trees grown in Rotoehu Forest, New Zealand (Jones et al. 2010). The lower growing temperature might contribute to the lower density of the New Zealand-grown trees as warmer climates were shown to increase wood density in *E. grandis* (Thomas et al. 2007).

Table 1
Summary statistics of *P. radiata* and *E. globoidea* machinability data. CV: coefficient of variation. Significant differences between species on the 0.05 level are highlighted in bold

		***Eucalyptus globoidea* n = 37**				***Pinus radiata* n = 49**				
		Mean	**CV**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**	**P-value**
Density (kg/m^3)		723.3	9%	553.7	872.8	460.9	9%	372.4	548.3	**< 2.2e-16**
Moisture content (%)		12.8	3%	12.1	13.5	12.0	7%	10.2	13.6	**1.834e-08**
Planing	0.8 cuts/mm	1.9	46%	1	4	1.9	39%	1	4	0.8515
Sanding	1.2 mm	5.0	0%	5	5	1.0	0%	1	1	**< 2.2e-16**
Boring	Entry	1.0	0%	1	1	1.5	38%	1	3	**6.283e-08**
	Hole	1.2	32%	1	2	3.1	23%	2	5	**< 2.2e-16**
	Exit	3.3	32%	2	5	4.1	15%	3	5	**3.305e-05**
	Overall	3.3	32%	2	5	4.1	15%	3	5	**2.401e-05**
Mortising	Entry	2.5	32%	1	4	3.4	27%	2	5	**4.535e-06**
	Side grain	2.5	22%	2	4	3.0	16%	2	4	**0.0002647**
	End grain	2.4	21%	2	3	4.4	11%	3	5	**< 2.2e-16**
	Exit	3.5	16%	3	5	4.8	9%	3	5	**< 2.2e-16**
	Overall	3.6	16%	3	5	4.8	8%	4	5	**< 2.2e-16**
Grooving	Side grain	1.4	40%	1	3	2.6	20%	1	3	**< 2.2e-16**
	Corner	1.5	35%	1	2	2.6	19%	2	3	**< 2.2e-16**
	End grain	2.0	8%	2	3	3.0	18%	2	4	**< 2.2e-16**
	Exit	2.9	24%	1	4	3.0	23%	2	5	0.5387
	Overall	3.0	22%	2	4	3.3	16%	3	5	**0.005251**
Edging	Side grain	1.2	59%	1	5	2.1	25%	1	3	**8.592e-09**
	Corner	2.9	42%	1	5	2.6	34%	1	5	0.1267
	End grain	2.1	27%	2	5	2.9	8%	2	3	**5.208e-10**
	Overall	3.1	38%	2	5	3.1	17%	2	5	0.8414
Turning	Wedge	2.2	83%	1	5	2.5	78%	1	5	0.5069

		Eucalyptus globoidea n = 37				*Pinus radiata* n = 49				
	Convex	2.8	51%	1	5	2.9	58%	1	5	0.8597
	Flat	2.7	58%	1	5	3.1	49%	1	5	0.1953
	Concave	2.6	60%	1	5	2.8	63%	1	5	0.7284
	Overall	2.9	47%	2	5	3.2	48%	1	5	0.4370

The mean equilibrium moisture contents at 65% relative humidity and 20°C were with 12.8% for *E. globoidea* and 12% for *P. radiata* boards (12%) in the expected range Table 1. The variation was low (*E. globoidea* CV – 3% and *P. radiata* CV = 7%), indicating sufficient equilibration.

3.1 Planing

No statistically significant difference was found between the surface finishes of *E. globoidea* and *P. radiata* after planing to 1.6 mm depth at 0.8 knife cuts/mm (Table 1). Both wood species planed well (mean visual grade of 1.9 (Table 1) and a machine score of ~ 80% Table 2)). This was consistent with *P. radiata*'s previously reported good planing characteristics (Young 1988).

Table 2
Overall machine scores for *E. globoidea* and *P. radiata* according to (ASTM, 2017)

Eucalyptus globoidea				
n = 37	**Grade 1**	**Grade 2**	**Grade 3**	**Machine Score**
Planing	15	13	-	76%
Sanding [a]	0	0	-	0%
Boring	0	10	-	27%
Mortising	0	0	17	46%
Grooving	0	8	-	22%
Edging	0	16	-	43%
Turning	0	25	-	68%
Pinus radiata				
n = 49	**Grade 1**	**Grade 2**	**Grade 3**	**Machine Score**
Planing	16	25	-	84%
Sanding	46	0	-	100%
Boring	0	0	-	0%
Mortising	0	0	0	0%
Grooving	0	0	-	0%
Edging	0	1	-	2%
Turning	5	18	-	47%

[a] Excellent sanding finish can be achieved at 0.5 mm instead of 1.2 mm depth.

3.2 Sanding

Consistent with previous reports all *P. radiata* boards sanded to a Grade of 1 finish (Young 1988). *E. globoidea* boards were almost impossible to sand with the machine settings prescribed in the standard (ASTM, 2017) as the sandpaper was clogged-up after sanding less than a meter causing surface charring (Fig. 1). Similar observations were made for other dense and durable eucalypts (Belleville et al. 2016).

The *E. globoidea* boards were significantly denser than the *P. radiata* boards (Table 1), implying more material to be removed by the sandpaper at a given time resulting in more friction-induced heat. Reducing the sanding depth from 1.2 mm to 0.5 mm resulted in Grade 1 finishes for subsequent *E. globoidea* boards, consistent with what was reported for other high-density eucalypts (Belleville et al. 2016). Consequently, *E. globoidea* can be sanded to the same excellent surface quality as sanded *P. radiata* if surface defects are not deeper than 0.5 mm or by repeating the procedure (Fig. 2). Apart from significantly larger density, *E. globoidea* heartwood contains extractives (Iyiola et al. 2022), which could have contributed to the clogging-up of the sandpaper.

3.3 Boring

Boring finishes were significantly better for *E. globoidea* than for *P. radiata* (Tables 1 and 2). The major defect was occurring during the exit of the drill (Tables 1 and 3). In contrast to *E. globoidea*, where the inside of the hole machined well, frequent defects were found for *P. radiata* at this location (Tables 1 and 3). The difficulty with boring *P. radiata* was unexpected considering the published rating of 4 out of 5 (Young 1988) and potentially due to more stringent grading and/or deviation from the standard in terms of RPM and borer type. An effect of borer type on drilling grades of eucalypts was reported (Belleville et al. 2016).

Table 3
Machinability scores for selected processing features of *E. globoidea* and *P. radiata*. Problematic processing features are highlighted bold

		Eucalyptus globoidea **n = 37**	***Pinus radiata*** **n = 49**
Boring	Entry	100%	96%
	Hole	100%	**18%**
	Exit	**27%**	**0%**
Mortising	Entry	84%	61%
	Side	97%	90%
	End	100%	**0%**
	Exit	**54%**	**2%**
Grooving	Side	97%	37%
	Corner	100%	37%
	End	97%	**12%**
	Exit	**22%**	**20%**
Edging	Side	97%	78%
	Corner	**47%**	**55%**
	End	95%	**6%**
Turning	Wedge	70%	63%
	Convex	68%	61%
	Flat	70%	**47%**
	Concave	70%	63%

3.4 Mortising

Similar to boring, *E. globoidea* produced significantly better-quality mortising finishes than *P. radiata* (Tables 1 and 2). The known difficulty in mortising *P. radiata* (Kotlarewski et al. 2019; Young 1988) was reflected in the low mean grade (4.8 out of 5) and machine machining score of 0%. As for boring, the worst defect occurred for both species when the tool exited the piece (Tables 1 and 3). For *P. radiata*, additionally the end-grain inside of the hole was problematic.

3.5 Grooving

Grooving finishes were significantly better in *E. globoidea* (mean grade 3.0, machine score 22%) than for *P. radiata* (mean grade 3.3, machine score 0%) (Tables 1 and 2). While the interior side- and end-grain faces machined well for *E. globoidea*, defects mainly occurred when the tool exited the piece (Tables 1 and 3). Tool exit was also problematic for *P. radiata*, which, in line with mortising, showed additional difficulties with the interior end-grain face of the groove. Therefore, *E. globoidea* 'exit' defects should be avoidable by employing backing pieces (Belleville et al. 2016) or starting the grooving process from both ends and meeting in the interior.

3.6 Edging

While the mean edging grade for the two species was the same (Table 1), the machine score was significantly better for *E. globoidea* (Table 2). The main reason for the worse performance of *P. radiata* was the end-grain surface, which had a machine score of 6% compared to the 95% for *E. globoidea* (Table 3). For both species, the sharp corner had a machine score of ~ 50%, being the limiting factor for *E. globoidea*. Improved corner finishes were reported for high density eucalypts by cutting against the feed direction (Belleville et al. 2016).

3.7 Turning

No statistically significant difference in the turning grades was found between the two species (Table 1). The higher machine scores of 70% for *E. globoidea* compared to the 50–60% of *P. radiata* were encouraging (Tables 2 and 3), in particularly as *P. radiata* is typically known to turn well (Young 1988). The different observation for average turning grade and machine score of the two species indicated that they differed in the proportion of 'extreme' (i.e., acceptable and completely failed) samples. Turning in this assessment resulted in frequent complete torsion failure of the samples in the lathe, likely caused by a suboptimal clamping method.

4 Conclusion

This study has confirmed that New Zealand grown *E. globoidea* heartwood machines equally well or better than *P. radiata*, except for sanding, which can be remedied by reducing the sanding depth. Consequently, solid wood processors working with *P. radiata* will not need to invest in new machinery when working with *E. globoidea*. This should give confidence to forest growers to invest in planting this emerging species. The generally good machinability of *E. globoidea* was consistent with reports for other plantation-grown higher density eucalypts (Belleville et al. 2016). In contrast, plantation-grown nondurable, medium density eucalypts (*E. nitens* and *E. globulus*) were shown more challenging to machine than *P. radiata* (Kotlarewski et al. 2019).

Optimisation of the machining parameters can be expected to improve the machine scores, for example for grooving having two entry points and no exit should avoid most defects.

Declarations

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Author contributions

Conceptualization: Clemens Altaner; Methodology: Hamish Scown, Clemens Altaner, Thomas Lim; Formal analysis and investigation: Hamish Scown, Clemens Altaner; Writing - original draft preparation: Hamish Scown; Writing - review and editing: Clemens Altaner, Hamish Scown, Thomas Lim; Funding acquisition: Clemens Altaner; Resources: Clemens Altaner, Thomas Lim; Supervision: Clemens Altaner, Thomas Lim.

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Figures

Figure 1

Left: sandpaper after sanding the 3rd *E. globoidea* board. Note: the gummed-up and charred 120-grit sandpaper. Right: the first, second and third sanded *E. globoidea* boards after sanding-off 1.2 mm (left to right). Note the burn marks on the surface

Figure 2

Left: *P. radiata* boards sanded to a depth of 1.2 mm. Right: *E. globoidea* boards sanded to a depth of 0.5 mm