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Sawing and grade recovery of 25-year-old *Eucalyptus fastigata*, *E. globoidea*, *E. muelleriana* and *E. pilularis*

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Abstract

The processing characteristics of 25-year-old *Eucalyptus fastigata* Deane et Maiden, *E. globoidea* Blakely, *E. muelleriana* Howitt and *E. pilularis* Sm. from Rotoehu Forest, New Zealand, were evaluated to determine if these species could be used to produce high-quality timber on shorter rotations. The butt- and second logs of 15 trees of each species were quarter-sawn and flat-sawn respectively, and the boards assessed for shrinkage and distortion, visual and mechanical properties, and surface hardness.

Growth-stress release during sawing, combined with end-checking during drying, resulted in board end-splitting that reduced the sawn recovery in *E. fastigata* compared with the other species, and produced high levels of crook in the quarter-sawn boards of all species. There was no surface checking and little or no drying collapse and internal checking.

The proportions of visual clears and No.1 cuttings grades were low, particularly for *E. muelleriana* and *E. pilularis*, due to the presence of knots. The boards of all species had high values of density, modulus of elasticity and surface hardness, and machine stress grades of MSG10 to MSG15.

These species have the potential to produce high-quality timber on 25-year rotations, but pruning will be required to improve visual grades so that a higher proportion of boards can be used in appearance applications.

Keywords: wood properties; quarter-sawing; flat-sawing; drying; grading, *Eucalyptus fastigata*; *Eucalyptus globoidea*; *Eucalyptus muelleriana*; *Eucalyptus pilularis*.

Introduction

The choice of eucalypts for solid-wood products requires species with growth- and wood-quality characteristics that are suited to producing logs that are easily sawn and capable of producing good proportions of clears and cuttings grade timber on relatively short rotations.

The stringybark species *Eucalyptus globoidea* Blakely and *E. muelleriana* Howitt, the closely related species *E. pilularis* Sm., and the ash species *E. fastigata* Deane et Maiden, have a reputation for good health and growth and ease of processing (Haslett et al., 1984; Miller et al., 2000; Shelbourne et al., 2002, 2003). They are less affected by growth stresses and are easier to saw and dry than many other eucalypt species. Their processing characteristics are, however, based on studies of the sawing and drying properties of wood from 40- to 55-year-old trees

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(Kininmonth et al., 1974; Gibson, 1976; J. M. Harris, unpublished results). The smaller sizes and steeper growth-stress gradients of short-rotation logs place greater demands on the wood-quality characteristics than in older trees (Haslett, 1988a, Nolan et al., 2005), and can have a major impact on the sawing strategies and the distortion and drying degrade. Therefore, the processing characteristics of these eucalypt species needed to be evaluated at a younger age.

The quarter-sawing and flat-sawing patterns are the two main sawing strategies used to mitigate distortion and drying degrade. Quarter-sawing minimises surface- and internal checking in species prone to drying collapse, but incurs greater losses in small-diameter logs due to growth-stress related distortion. Flat-sawing is faster and minimises the effects of growth stresses, but surface checking and cupping can occur in species with high differential shrinkage (Nolan et al., 2005).

The clearfelling of a 25-year-old species demonstration trial at Rotoehu Forest provided the opportunity to evaluate the solid-wood processing characteristics of four eucalypt species. The 2.7 metre-length butt logs were quarter-sawn, and the 2.7 metre-length second logs were flat-sawn, for 15 trees of each species. The 40 mm-thick flitches were air-dried, re-sawn to final width, and kiln-dried. The boards were assessed for shrinkage and distortion, visual and mechanical properties, and surface hardness. The eucalypt species were compared on the basis of the individual tree-, log- and board properties.

Materials and Methods

Tree Selection

The 15 trees of each of 25-year-old *Eucalyptus fastigata*, *E. globoidea*, *E. muelleriana* and *E. pilularis* were selected on the basis of good form and growth from a 1980 species demonstration planting in Compartment 4, Rotoehu Forest, Bay of Plenty (lat. 37°54'S, long. 176°30'E, altitude 100 m). The species demonstration planting included both New Zealand and Australian seedlots (Table 1), and comprised adjacent unreplicated blocks of 300 to 600 trees of each species. The initial spacing was 3 × 2 m (1650 stems/ha) with areas per species of ca. 0.18-0.3 ha. There was no pruning or thinning, but some self-pruning and natural mortality had occurred.

The climatic conditions for the Rotoehu Forest site were: mean annual temperature 13.5 °C, mean temperature of the warmest month 18.3 °C, mean temperature of the coldest month 8.3 °C, mean minimum temperature of the coldest month 2.6 °C, mean annual rainfall 1751 mm (Leathwick et al., 2002).

Tree and Log Assessment

The trees were measured at breast height for diameter over bark, outerwood basic density using two 5 mm increment cores (Haslett & Young 1990), and acoustic velocity (IML hammer, Kennesaw, GA, USA). After felling, each stem was cross-cut at 5.5 m height and the acoustic velocity of the 5.5 m length butt log was measured using a Director HM200 (Fibre-gen, Christchurch, New Zealand). Log end-splitting was assessed 48 hours after cross-cutting on both the butt- and top end of each 5.5 m length log. The log end-splitting scores were calculated from the measurements of split length and width using the procedure described by Conradie (1980).

The 5.5 m length butt logs were cross-cut at the sawmill into 2.7 m length butt and second logs. Discs were taken at 2.7 and 5.5 m heights for the measurement of wood basic density and heartwood content. The wood basic density was measured gravimetrically using two diametric pith-to-bark sectors cut from each disc, and the heartwood content was measured as a percentage of the disc area (Haslett & Young 1990).

Sawing

The 2.7 m length butt and second logs were cut into 40 mm thick flitches and boards, without the use of straightening cuts. This was done to evaluate the distortion that occurred as a result of growth-stress release during sawing, and the changes that occurred

TABLE 1: Eucalypt species seedlots and numbers of trees planted.

Species	Seedlot	Number of trees
E. fastigata	HO. 78/18 McAlpine, Taranaki, NZ	500
E. globoidea	R. 58/624 Hewitt, Omariawa, NZ, blanked with 1/0/79/12 Glenbervie, Cpt 19, NZ	500
E. muelleriana	Wn. 63/431 Kamano, Fielding, Manawatu, NZ	600
E. pilularis	HO. 70/748 Coffs Harbour, NSW, blanked with 1/0/63/915 Riverhead, NZ	300

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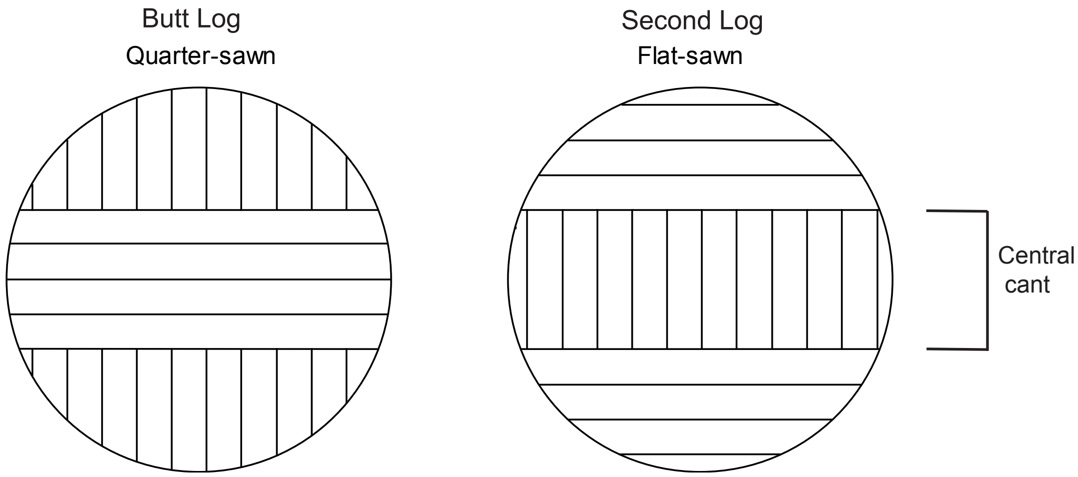

FIGURE 1: Sawing patterns for the quarter-sawn butt logs and flat-sawn second logs.

during drying. The butt logs were cut using a variation of the through-and-through sawing pattern to increase the proportion of quarter-sawn boards (Figure 1). The butt logs were cut in half through the pith and 40 mm thick flitches cut parallel to the first cut using a Woodmizer bandsaw mill. The two slabs from the top and bottom were cut into 40 mm thick flitches at right angles to the first cut using a vertical bandsaw with a feed belt. The second logs were cut using a cant-sawing pattern to give a high proportion of flat-sawn boards (Figure 1). The second logs were cut into 40 mm thick flitches from one side and then the opposite side, leaving a central cant which was cut into 40 mm thick boards at right angles to the first cut, using a Woodmizer bandsaw mill.

The flitch[1] movement off the saw, as a result of growth-stress release, was measured on the butt logs for the first cut through the pith. The flitch movement was measured at the log end when the bandsaw blade had cut one metre along the length of the log.

The flitches and boards were measured for length, width, thickness, crook[2] and bow[3] immediately after sawing.

Drying

The 40 mm thick flitches and boards were placed in filleted stacks in an open-sided barn and air-dried for 12 months to 20-28% moisture content. The air-dried flitches were re-sawn to nominal board widths of 100, 125, 150, 200, 250, 300 mm, and docked to remove end-splitting.

The volume recovery of air-dried boards was determined using the actual board sizes and docked lengths, and calculated as a percentage of the green log volume.

A random sample (32%) of the air-dried boards from the butt- and second logs of each tree were kiln-dried to 12-14% moisture content in a Windsor 2.4 m experimental kiln (capacity 3 m³). The kiln schedule was: 1 hour heat-up, 4 hours steam re-conditioning at 98/98 °C (dry bulb/wet bulb), 64 hours drying at 70/60 °C, 4.5 hours final steaming at 75/74 °C for stress release and moisture content equalisation. The stack was weighted during kiln-drying using a loading of 500 kg/m^2.

The air-dried and kiln-dried boards were weighed and measured for length, width, thickness, crook and bow. The width and thickness shrinkage of the boards was calculated using the equation:

$$S = \frac{G_{width} - D_{width}}{G_{width}} \times 100 \qquad [1]$$

[1] Flitch - an unedged piece of lumber;
[2] Crook - deviation edgewise from a straight line drawn from end to end of a board;.
[3] Bow – deviation flatwise from a straight line drawn from end to end of a board.

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where: S is the shrinkage (%), G_{Width} is the green-board width or thickness (mm), D_{Width} is the air-dried or kiln-dried board width or thickness (mm).

The density of the kiln-dried boards was calculated using the equation:

$$\rho = \frac{D_{weight}}{D_{volume}} \quad [2]$$

where: ρ is the kiln-dry density (kg/m³), D_{Weight} is the kiln-dried weight (kg), D_{Volume} is the kiln-dried volume (m³).

The kiln-dried boards were assessed for internal checking by cross-cutting at approximately 350 mm from the top end of the quarter-sawn boards and lower end of the flat-sawn boards to avoid the effects of drying from the end-grain of the boards, and to sample similar positions in the tree stem for the two sawing methods.

Visual Grading

The undressed air-dried boards were appearance-graded in accordance with NZS 3631:1988. The appearance grades were: clears, No.1 cuttings, No.2 cuttings, No.3 cuttings, box (McKenzie et al., 2000). The volume recovery of each appearance grade was determined using the actual board sizes and docked lengths, and calculated as a percentage of the green log volume. The presence or absence of kino in each air-dried board was also recorded.

Stiffness Grading

The kiln-dried boards were evaluated for acoustic modulus of elasticity ($MOE_{acoustic}$) using the acoustic velocity (measured with a Director HM200) and the board density. The acoustic modulus of elasticity ($MOE_{acoustic}$) was calculated using the equation:

$$MOE_{acoustic} = \rho V^2 \quad [3]$$

where: V is the acoustic velocity (m/s), ρ is the kiln-dried density (kg/m³).

The kiln-dried boards were tested in bending to determine the modulus of elasticity (MOE_{joist}) as a joist. The boards were tested on edge under monotonic and third-point loading to a preset mid-span deflection (Figure 2) in a Grade 1 Baldwin Universal test machine. The total span was 2340 mm as recommended in AS/NZS 4063:1992. The slope of the linear section of the load/deflection data at mid-span and the maximum load at the preset deflection were recorded. The modulus of elasticity (MOE_{joist}) as a joist was calculated using the equation:

$$MOE_{joist} = (P / \Delta) \times \frac{23L^3}{108bd^3} \quad [4]$$

where: P is the maximum load (kN), Δ is the deflection (mm), (P / Δ) is the slope of the linear portion of the load / deflection graph (kN/mm), b is the section thickness (mm), d is the section depth (mm), L is the test span (mm), (Figure 2).

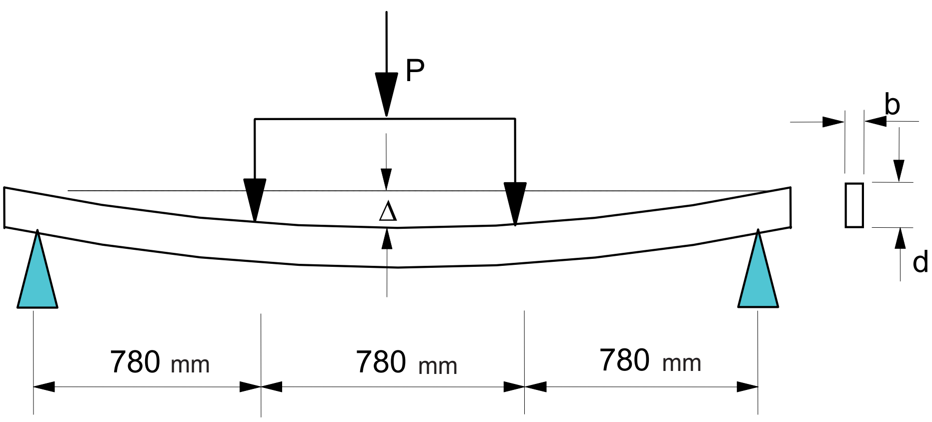

FIGURE 2: Bending test configuration for measurement of modulus of elasticity (MOE_{joist}) as a joist.

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The kiln-dried boards were assigned to machine stress grades (MSG) by ranking them for modulus of elasticity (MOE_{joist}) and allocating them to groups with average values of 15 GPa (MSG 15), 12 GPa (MSG 12), and 10 GPa (MSG 10).

Wood Hardness

The Janka hardness of the wood was measured on the wide faces of the kiln-dried boards using the ASTM Standard D143-94 (1999). The kiln-dried boards were sampled from both the butt- and second log of each tree.

Statistical Analysis

The standing-tree, log-, disc- and board properties of each species were compared for the butt- and second logs using one-way analysis of variance (ANOVA) with the SAS Proc GLM (SAS Institute, 2000) and the model:

$$y_{ij} = \mu + s_i + e_{ij}$$

where: y_{ij} denotes the variable measured on eucalypt species i; μ is the overall population mean; s_i represents the fixed effect of the eucalypt species, and e_{ij} represents the error term for the measurements.

The SAS Proc GLM (SAS Institute, 2000) MEANS statement and LSD option, which performs pairwise t-tests, equivalent to Fisher's least-significant-difference LSD test in the case of equal cell sizes, was used to provide multiple comparisons of the eucalypt species means.

The correlation between the standing-tree (IML Hammer) and log (Director HM200) acoustic velocity was evaluated using SAS Proc Corr (SAS Institute, 2000).

The comparison of the log taper and board hardness for the four eucalypt species were evaluated after adjustment for differences in log volume and board density, respectively, using analysis of covariance with the SAS Proc GLM procedure (SAS Institute, 2000).

Results and Discussion

Standing Tree Properties

The growth of the eucalypt species at Rotoehu Forest was strongly influenced by the climatic conditions of the site. The diameter growth of the trees was largest for *E. fastigata*, smaller for *E. globoidea*, and smallest for *E. muelleriana* and *E. pilularis* (Table 2). *E. fastigata* is well adapted to coastal North Island sites (Miller et al., 2000; Shelbourne et al., 2000) and the climatic conditions at Rotoehu Forest were well within the growth requirements for this species (Booth & Pryor 1991). *Eucalyptus globoidea* appeared to be well adapted to the site, but the slower growth of *E. muelleriana* was an indication of the marginal climatic conditions for this species. The mean annual temperature of the Rotoehu Forest site (13.5 °C) was at the low end of the natural range for *E. muelleriana* in Australia (Austin et al., 1990). The mean annual temperature (13.5 °C), and the mean minimum temperature of the coldest month (2.6 °C) at Rotoehu Forest were both lower than the accepted growth requirements for *E. pilularis* (Booth & Pryor, 1991). This was reflected in the poor survival and slow growth of this species.

The breast-height outerwood basic density was high for all the species (Table 2). The mean basic density of the *E. pilularis* at Rotoehu Forest (540 kg/m³) was the same as that of re-growth *E. pilularis* in NSW, Australia at age 30 years (Bamber & Curtin, 1974).

The breast-height outerwood acoustic velocity, measured using the IML Hammer, was higher for *E.*

TABLE 2: Standing-tree measurements at breast height showing species averages with ranges of tree values in brackets. Average values followed by the same letter do not differ significantly (p > 0.05).

Species	Diameter over bark, mm	Outerwood basic density, kg/m³	Acoustic velocity, km/s
E. fastigata	525 (415-628) a	539 (477-610) a	2.7 (2.6-3.1) a
E. globoidea	472 (395-575) b	543 (442-620) a	2.5 (2.2-2.8) b
E. muelleriana	427 (381-485) c	546 (507-597) a	2.5 (2.3-2.8) b
E. pilularis	398 (350-492) c	540 (484-602) a	2.5 (2.2-2.8) b

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fastigata than *E. globoidea*, *E. muelleriana* and *E. pilularis* (Table 2). The acoustic velocity for a given density provides an indirect measure of the microfibril angle of the wood, but it can also be affected by the moisture content and the grain angle of the wood. The individual-tree values for a species can vary widely. *Eucalyptus nitens* trees aged 23 years in Kinleith Forest had a higher average breast-height outerwood acoustic velocity (3.0 km/s) than any of the four species in this trial (2.5 – 2.7 km/s), but the individual *E. nitens* values spanned the range of the four species in this study (McConnochie et al., 2004).

Log- and Disc Properties

The volume of the 5.5 m length butt logs was significantly greater for *E. fastigata* than for *E. globoidea*, *E. muelleriana* and *E. pilularis* (Table 3). The average volume of the *E. fastigata* butt logs was 42 to 51% greater than those of the other species. The taper of the butt logs was greater for *E. fastigata* than for the other three species studied, but this was strongly influenced by the log volume. When compared at the same log volume, there was no difference in the taper of the butt logs among the four species, details not shown.

The basic density of butt logs at 2.7 m height was similar for all four species (Table 3). The basic density increased with height from 2.7 to 5.5 m, and was slightly higher at 5.5 m for *E. globoidea* and *E. muelleriana*. Comparison with previous New Zealand studies showed: the basic density of *E. fastigata* was high compared with 43-year-old trees from Kaingaroa Forest (J. M. Harris, unpublished results); the basic density of *E. globoidea* was low compared with 40-year-old trees from Whakatane (J. M. Harris, unpublished results); and, the basic density of E. muelleriana was similar to 45-year-old trees from Athenree Forest (G. D. Young, unpublished results).

The acoustic velocity of the butt logs, measured using the Director HM200, was higher for *E. fastigata* than *E. globoidea*, *E. muelleriana* and *E. pilularis* (Table 3). The log measurements of acoustic velocity were consistent with the standing-tree measurements (Table 2) with a moderate correlation between the IML Hammer outerwood and Director HM200 log acoustic velocity for the combined four species ($r = 0.67$, $p < 0.01$).

The heartwood content of the butt logs at 2.7 m height was high (greater than 80%) for all four species (Table 3). Although the 25-year-old trees in this study were younger than those in previous studies, the heartwood contents measured here were similar to those observed in 40-year-old trees of *E. globoidea* from Whakatane (J. M. Harris, unpublished results) and 45-year-old trees of E. muelleriana from Athenree Forest (G. D. Young, unpublished results).

The log end-splitting that occurred after the butt logs were cut was greater for *E. fastigata* than *E. globoidea*, *E. muelleriana* and *E. pilularis* (Table 3). Log end-splitting is associated with the release of growth stresses on cross-cutting (Boyd, 1950; Okuyama et al., 2004). The ash eucalypts such as *E. fastigata* have moderate growth stresses (Haslett, 1988b), while the stringybark eucalypts such as *E. globoidea* and *E. muelleriana* have only slight growth stresses (Haslett, 1990). The log end-splitting observed in this study was consistent with the growth stresses of these species. The log end-splitting of the *E. pilularis* butt logs was consistent with the very low incidence of end-splitting observed in logs from a 50-year-old *E. pilularis* tree from Riverhead Forest (Gibson, 1976).

The flitch movement during the first saw-cut in the 2.7 m length butt logs was similar for all four species studied here (Table 3). The amount of flitch movement during sawing is associated with the release of growth stress and was relatively small compared with the flitch movement in the butt logs of 23-year-old *E. nitens* trees from Kinleith Forest (McConnochie et al., 2004). *Eucalyptus globoidea,* in particular, cut well and was stable during sawing, a characteristic that has also been observed for *E. globoidea* in South Africa (Bolza & Keating, 1972).

Board Grade Recovery

The air-dry timber recovery as a percentage of the log volume was lower for *E. fastigata* than for *E. globoidea*, *E. muelleriana* or *E. pilularis*. The total volume of air-dry timber was higher for *E. fastigata* due to its larger log volume than for the other three species (Table 4). The end-splitting of the logs prior to sawing, and the increase in end-splitting during air-drying and the associated docking losses reduced the air-dry timber recovery of *E. fastigata* compared with the other species. An earlier sawing study of 29-year-old *E. fastigata* from Kaingaroa Forest (McKenzie et al., 2000) had a similar air-dry timber recovery, and also showed losses due to end-splitting.

The visual board grades differed considerably for the four species. *Eucalyptus fastigata* and *E. globoidea* produced a higher percentage of clears and No.1 cuttings, while *E. muelleriana* and *E. pilularis* produced a higher percentage of shorter No.3 cuttings (Table 4 and Figure 3). *Eucalyptus fastigata* and *E. globoidea* demonstrated the ability to produce a higher proportion of clears from the unpruned stand, which has been previously shown for 36-year-old *E. fastigata* trees from Oakura in Taranaki (Kininmonth et al., 1974).

The incidence of kino in the boards was low, but higher for *E. fastigata* than the other three species. Kino was present in 6% of the *E. fastigata* boards, 1% of the *E. globoidea* boards, and in less than 1% of the *E. muelleriana* and *E. pilularis* boards. *Eucalyptus fastigata*

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TABLE 3: Log and disc measurements showing species averages with ranges of tree values in brackets. Average values followed by the same letter do not differ significantly ($p > 0.05$)

Species	Volume 5.5 m log, m³	Taper 5.5 m log, mm/m	Basic density at 2.7m, kg/m³	Basic density at 5.5m, kg/m³	Acoustic velocity 5.5 m log, km/s
E. fastigata	0.8 (0.4-1.3) a	20 (12-47) a	524 (465-594) b	542 (488-588) c	3.7 (3.3-3.9) a
E. globoidea	0.5 (0.3-0.7) b	16 (8-31) ab	543 (450-635) ab	574 (463-654) ab	3.4 (3.1-3.8) b
E. muelleriana	0.4 (0.2-0.6) b	17 (13-24) a	565 (519-612) a	587 (525-625) a	3.5 (3.0-3.8) b
E. pilularis	0.4 (0.3-0.6) b	12 (8-22) b	541 (470-642) ab	549 (494-653) bc	3.5 (3.0-3.8) b
	Heartwood at 2.7 m, %	**End-splitting score at butt**	**End-splitting score at 5.5m**	**Flitch movement mm**	
E. fastigata	82 (63-91) a	12 (2-22) c	12 (6-20) b	34 (19-49) a	
E. globoidea	81 (64-96) a	7 (3-12) ab	9 (4-14) a	35 (27-54) a	
E. muelleriana	84 (69-90) a	6 (2-12) a	9 (6-12) a	34 (25-41) a	
E. pilularis	85 (80-89) a	10 (2-18) b	9 (4-15) a	34 (26-55) a	

TABLE 4: Visual board grade recovery of air-dried timber in cubic metres (m³), and as a percentage of the log volume. Species average total values followed by the same letter do not differ significantly ($p > 0.05$).

Species	Clears	No.1 Cuttings	No.2 Cuttings	No.3 Cuttings	Box	Total
Recovery, m³						
E. fastigata	1.4	1.1	0.7	1.5	0.6	5.3 a
E. globoidea	1.3	0.7	0.6	0.9	0.2	3.8 b
E. muelleriana	0.3	0.4	0.8	1.9	0.2	3.6 b
E. pilularis	0.2	0.4	0.6	1.6	0.5	3.3 b
Recovery, %						
E. fastigata	29	19	16	25	11	44 b
E. globoidea	34	19	17	24	6	55 ab
E. muelleriana	9	10	22	52	7	58 a
E. pilularis	9	13	16	46	16	57 a

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from Rotoehu Forest had a much lower incidence of kino than has been found at other New Zealand sites. Kino was present in 40% of the boards of 29-year-old *E. fastigata* from Kaingaroa Forest (McKenzie et al., 2000) and 34% of the boards of 36-year-old *E. fastigata* from Oakura in Taranaki (Kininmonth et al., 1974). Reasons for these differences in *E. fastigata* from different sites are unknown.

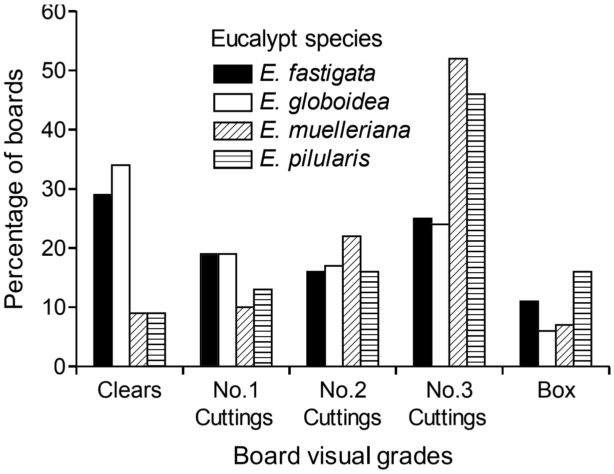

FIGURE 3: Board visual grades for the eucalypt species.

Shrinkage and Distortion

The shrinkage of both air-dried and kiln-dried boards was moderate for all four species (Table 5). These four species are less prone to drying collapse than other eucalypts, and the absence of large shrinkage changes following steam-reconditioning and kiln-drying suggests there was little drying collapse present in the air-dried boards. The kiln-dried shrinkage was similar to previous studies for these species (Haslett, 1988b, 1990) and tended to be intermediate between the tangential and radial shrinkage, reflecting the presence of intermediate as well as quarter-sawn and flat-sawn boards.

The incidence of internal checking in the kiln-dried boards was very low in all the species. Internal checks were present in 3% of the *E. fastigata* and *E. globoidea* boards, and were absent from the *E. muelleriana* and *E. pilularis* boards. The 3% internal checking of *E. fastigata* from Rotoehu Forest was lower than the 8% observed for kiln-dried boards from 29-year-old *E. fastigata* from Kaingaroa Forest (McKenzie et al., 2000).

The board distortion in the form of crook and bow was strongly influenced by the sawing pattern, and occurred as a result of growth stress release during sawing. The growth stress release took the form of

TABLE 5: Shrinkage of the air-dried and kiln-dried boards from the butt and second logs showing species averages with ranges of log values in brackets. Average values followed by the same letter do not differ significantly ($p > 0.05$).

Species	Shrinkage – air-dried width, %	Shrinkage – air-dried thickness, %	Shrinkage – kiln-dried width, %	Shrinkage – kiln-dried thickness, %
Butt log				
E. fastigata	4.1 (2.5-5.9) c	3.3 (0.9-5.7) bc	3.4 (1.5-5.2) a	3.5 (1.8-6.3) a
E. globoidea	3.6 (2.6-5.1) ab	4.2 (1.6-8.0) c	3.3 (1.6-5.6) a	4.0 (1.7-9.0) a
E. muelleriana	2.6 (2.0-3.4) a	2.2 (0.7-4.2) a	2.9 (2.4-3.9) a	3.3 (0.4-6.8) a
E. pilularis	3.4 (2.4-4.7) b	3.2 (1.0-4.4) b	3.5 (2.0-4.9) a	3.5 (1.3-7.0) a
Second log				
E. fastigata	5.9 (4.5-10.6) a	6.8 (2.9-11.4) a	6.7 (4.3-12.1) a	7.8 (4.4-11.5) a
E. globoidea	4.6 (2.4-6.4) b	5.0 (2.1-8.0) bc	4.3 (3.2-5.8) b	5.2 (0.0-11.8) b
E. muelleriana	3.5 (2.1-4.2) c	4.4 (3.0-5.8) c	4.6 (3.4-6.3) b	6.3 (2.2-9.0) ab
E. pilularis	4.0 (2.4-6.0) bc	6.0 (2.1-9.4) ab	4.8 (3.4-7.4) b	5.2 (2.0-7.6) b

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crook in the quarter-sawn boards, and bow in the flat-sawn boards. Crook is difficult to remove during drying, and was largely unchanged from the green to the air-dried and kiln-dried state in the quarter-sawn butt-log boards (Table 6). The crook was much lower in the flat-sawn second-log boards, and declined slightly from the green to kiln-dried state. Bow can be substantially reduced during drying by applying weight to the drying stacks, and declined from green to kiln-dried for the butt- and second log boards (Table 6). There was a slight increase in bow from the green to air-dried state for the second-log boards, which can be attributed to the lack of applied weight to the air-dried stacks, but this was reversed when weight was applied during kiln-drying.

The permitted grade limits for crook (NZS 3631:1988) were exceeded by many of the quarter-sawn butt-log kiln-dried boards, while all boards from the butt- and second logs were within permitted grade limits for bow. The percentage of kiln-dried boards exceeding grade limits for crook were 83, 65, 78 and 61% for the butt logs, and 17, 4, 15 and 5% for the second logs of *E. fastigata*, *E. globoidea*, *E. muelleriana* and *E. pilularis* respectively. Comparison with previous studies showed the board distortion for these species was lower than that of 23-year-old *E. nitens*, but larger than that for 55-year-old *E. fastigata*. The green quarter-sawn boards of 23-year-old *E. nitens* from Kinleith Forest (McConnochie et al., 2004) had an average crook of 16 mm, after adjustment to a 2.7 m length board (Simpson & Shelly, 2000). This suggests the growth stresses and the growth-stress release during sawing were larger in *E. nitens*. A mixture of quarter and flat-sawn kiln-dried boards of a 55-year-old tree of *E. fastigata* from Whakarewarewa Forest (Kininmonth et al., 1974) had a smaller range of crook than the 25-year-old *E. fastigata* in this study. This difference could be attributed to steeper growth-stress gradients in the smaller diameter *E. fastigata* trees of this study. The diameter of the logs affects the slope of the pith-to-bark growth stress gradient, with smaller-diameter logs having steeper gradients that accentuate board distortion (Haslett, 1988a).

Mechanical Properties and Surface Hardness

The density of the kiln-dried boards was high for all the species, but slightly higher for *E. globoidea* and *E. muelleriana* compared with *E. fastigata* and *E. pilularis* (Table 7). The density increased with height from the butt- to second logs for all species. Comparison with the density of kiln-dried boards from previous New Zealand studies showed the density of *E. fastigata* (629 kg/m^3) was similar to boards from 36-year-old trees from Oakura in Taranaki, and higher than boards of a 55-year-old tree from Whakarewarewa Forest; while the density of *E. muelleriana* was similar to boards from 25- to 30-year-old trees from Okaihau in

TABLE 6: Crook and bow in green, air-dried and kiln-dried boards from the butt and second logs showing species averages with ranges of log values in brackets. Average values followed by the same letter do not differ significantly ($p > 0.05$).

Species	Crook green, mm	Crook air-dried, mm	Crook kiln-dried, mm	Bow green, mm	Bow air-dried, mm	Bow kiln-dried, mm
Butt log						
E. fastigata	11 (5-18) a	12 (4-17) a	12 (3-18) a	7 (2-10) a	5 (2-11) a	1 (0- 3) a
E. globoidea	11 (5-20) a	10 (3-21) a	9 (0-29) a	8 (5-15) a	4 (2-10) a	1 (0- 5) a
E. muelleriana	10 (8-14) a	10 (7-14) a	10 (5-16) a	7 (4-11) a	5 (2- 9) a	1 (0- 4) a
E. pilularis	11 (8-16) a	11 (6-18) a	9 (3-19) a	8 (4-14) a	5 (2-11) a	1 (0- 4) a
Second log						
E. fastigata	5 (2- 9) a	3 (0- 8) a	2 (0- 6) a	4 (0- 8) a	6 (1-11) c	3 (0- 7) a
E. globoidea	6 (1-13) a	3 (0-10) a	1 (0- 7) a	6 (0-16) a	8 (0-17) b	4 (0-19) a
E. muelleriana	6 (0-13) a	5 (3-12) a	2 (0- 6) a	6 (1-11) a	11 (6-14) a	5 (0-10) a
E. pilularis	6 (1-15) a	5 (2-10) a	1 (0- 5) a	5 (0-10) a	8 (3-13) bc	3 (0-12) a

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Northland; and the density of *E. pilularis* was lower than the density of boards from a 43-year-old tree from Puhipuhi in Northland (Kininmonth et al., 1974). The *E. fastigata* seedlot used at Rotoehu Forest (Table 1) was obtained from the stand of trees at Oakura in Taranaki, which explains the high density of the *E. fastigata* kiln-dried boards in this study.

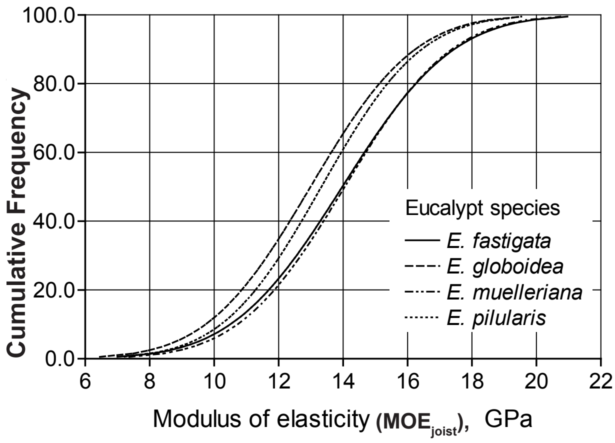

FIGURE 4: Cumulative frequency distribution of board modulus of elasticity (MOE_{joist}) for the eucalypt species.

The mean modulus of elasticity (MOE_{joist}) of the kiln-dried boards was high (12 – 16 GPa) for all four species tested (Table 7 and Figure 4). Comparison with in-grade tested, plantation-grown *E. globulus*, *E. nitens* and *E. regnans* in Australia showed the modulus of elasticity (MOE_{joist}) values obtained here were similar to those for 19- to 33-year-old *E. globulus* (Yang & Waugh, 1996a) but higher than 15- to 30-year-old *E. nitens* and *E. regnans* (Yang & Waugh, 1996b). The modulus of elasticity (MOE_{joist}) of the kiln-dried boards were equivalent to the machine stress grades MSG 10, MSG 12 and MSG 15 (Figure 5), indicating the boards of these species can be used in load-bearing applications.

The surface hardness of the kiln-dried boards was high for all the species, but slightly higher for *E. globoidea* and *E. muelleriana* compared with *E. fastigata* and *E. pilularis* (Table 7). The hardness was strongly influenced by the density of the boards, increasing with height from the butt- to second logs for all species. When compared at the same density, there was little difference in hardness among the four species. The hardness of the boards was similar to previous measurements of these species (Bier & Britton, 1999) after adjustments were made for differences in density.

TABLE 7: Mechanical properties, density and hardness of kiln-dried boards from the butt and second logs showing species averages with ranges of board values in brackets. Average values followed by the same letter do not differ significantly ($p > 0.05$).

Species	Kiln-dry density kg/m³	$MOE_{acoustic}$ GPa	MOE_{joist} GPa	Hardness kN
Butt log				
E. fastigata	629 (522-761) b	16 (11-20) a	14 (9-19) a	4.7 (2.6-8.0) b
E. globoidea	655 (497-806) a	13 (10-19) c	12 (9-18) c	5.5 (1.4-9.4) a
E. muelleriana	662 (585-755) a	14 (10-21) b	13 (9-18) ab	5.5 (3.4-8.2) a
E. pilularis	627 (510-755) b	14 (10-19) bc	13 (9-16) bc	4.6 (2.6-6.5) b
Second log				
E. fastigata	669 (547-870) b	19 (12-26) a	15 (9-21) ab	5.3 (3.1-8.3) b
E. globoidea	703 (540-883) a	17 (12-23) bc	15 (11-20) ab	6.1 (3.4-9.5) a
E. muelleriana	721 (637-796) a	18 (12-23) ab	16 (11-20) a	6.3 (4.8-8.3) a
E. pilularis	659 (552-725) b	16 (12-18) c	14 (10-17) b	5.7 (3.7-7.4) ab

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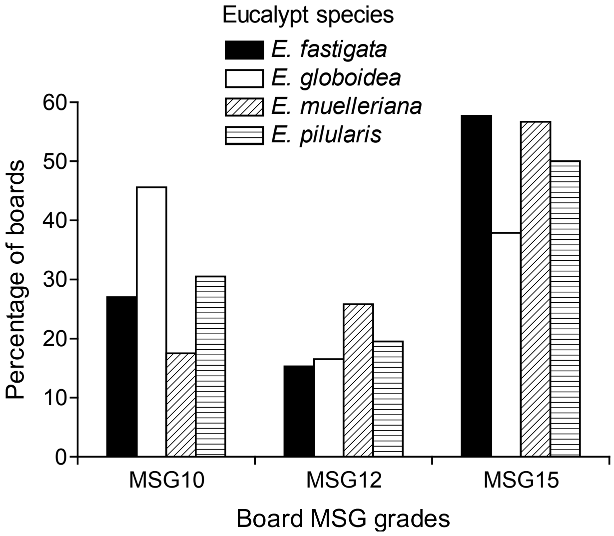

FIGURE 5: Board MSG grades for the eucalypt species, based on the modulus of elasticity (MOE_{joist}).

Conclusions

The eucalypt species *E. fastigata*, *E. globoidea*, *E. muelleriana* and *E. pilularis* have the potential to produce high-quality timber on 25-year rotations, with the main constraints being the presence of growth stress, and knots in unpruned stands.

Quarter-sawing and flat-sawing can be used with these species, but straightening cuts will be required for the majority of quarter-sawn boards to ensure the board crook, associated with growth-stress release during sawing, meets permitted grade limits. Shrinkage values for the steam-reconditioned and kiln-dried boards were moderate for these species, with no surface checking, and little or no drying collapse and internal checking.

The machine stress grades were high for the kiln-dried boards, but the visual grades were adversely affected by the presence of knots. Pruning will be required to increase the proportion of boards for use in appearance applications.

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