



Quality traits of plantation *Eucalyptus nitens* logs impacting volume and value recovery of structural sawn boards

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Abstract

Plantations of *Eucalyptus* species are planted and grown worldwide for short rotations and with limited silvicultural treatments mostly to produce pulplogs for the pulp and paper industry. These resources could be used as raw material for construction timber, to support the increasing need of renewable resources from the building sector. To use fast-grown *Eucalyptus* logs as a source of sawn timber log grading standards are needed, which can be developed accounting for log characteristics impacting sawn timber recovery. This study aims to examine the quality of fast-grown *Eucalyptus* logs and relate relevant log quality traits to sawn timber characteristics. Wood quality and log characteristics of forty-nine fast-grown *Eucalyptus* logs and the characteristics and structural properties of 268 sawn boards milled from those logs were investigated. Significant differences were found in wood quality characteristics from logs sourced from different positions in the stem. However, sawn boards did not differ in their wood quality traits according to log position, which influenced only the amount and type of knots on the board surface and some structural properties. Moreover, log characteristics including volume, taper, log end splits and stiffness significantly impacted important board recovery traits. The results of this study show that log characteristics such as volume, taper, log end splits and stiffness should be accounted for in log grading standards seeking to grade fast-grown *Eucalyptus* resources for different product classes.

1 Introduction

The use of timber as a construction material is becoming increasingly prevalent due to the many benefits of wood. The physical properties of wood are attractive to the construction industry, being light-weight with a high strength-to-weight ratio and having predictable fire behaviour (Wimmers 2017). Wood possesses thermal insulating properties (Liu et al. 2018) and is a sustainable, renewable building material (Ramage et al. 2017) that can be used in timber structures to replace concrete and steel, thus reducing emissions of greenhouse gasses (Crawford and Cadorel 2017). The demand for wood-based panels is increasing both for construction of new residential buildings and for renovation

of old structures, and this trend may help to meet targets of decreasing CO₂ emissions (Hildebrandt et al. 2017).

Wood-based panel constructions are mostly engineered wood products (EWPs), such as cross-laminated timber (CLT), glue-laminated timber (GLT) and laminated veneer lumber (LVL), which are highly optimised for pre-fabrication, decreasing the time needed for building construction and overall project costs (Hildebrandt et al. 2017; Kremer and Symmons 2018). The characteristics of the components of EWPs influence the quality and performance of the final panel, and EWP properties can be estimated from the properties of the layers composing the panels (Brandner et al. 2016; Derikvand et al. 2019b). Dimensions, structural properties and the presence of features are fundamental characteristics of structural boards composing the panels (Harte 2017), and dimensional stability and characteristics, such as checking, warping, and swelling, will affect the structural properties and the lamination of the final EWPs (Schmidt et al. 2019).

Sawn timber from softwood species is the main resource used for EWPs, but there is an increased interest in using hardwood species (Espinoza and Buehlmann 2018; Luedtke et al. 2015), especially of the genus *Eucalyptus*, which is

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widely planted across the globe (Dugmore et al. 2019; Derikvand et al. 2017). Characteristics of fast-grown *Eucalyptus* logs include small dimensions, low strength and stiffness, and the presence of unpruned branches, all of which impact the quality of the sawn timber. Timber from fast-grown *Eucalyptus* resources can have low dimensional stability, exhibit drying defects, splitting, and low structural properties (Jacobs 1955; Derikvand et al. 2018a; Ananías et al. 2014). These characteristics are related to the growth of the trees under short rotations without the application of silvicultural treatments. Traditionally, the main use of fast-grown *Eucalyptus* species is for the production of logs for the pulp and paper industry. Both decreased demand for fibre (Liao et al. 2017) and increased need for wood for timber products (Hakamada et al. 2017) have become determinant factors in considering alternative products for this resource (Wessels et al. 2020). However, targeted research is needed to understand how characteristics of the logs might impact the volume and value recovery of sawn material. To support the utilisation of the *Eucalyptus* resource for timber products it is necessary to determine the logs and sawn timber characteristics which might impact the recovery of products and their utilisation as structural boards for construction or as components of EWPs. The purpose of this work was to examine the quality of logs from fast-grown *E. nitens* plantations to understand the characteristics that impact the recovery of sawn timber. To achieve this aim the objectives of this study were to:

- i. Investigate the longitudinal variation in wood properties of the logs sourced from different positions in the stem.
- ii. Investigate the recovery rate and characteristics of the sawn boards from logs of different positions.
- iii. Examine the relationship between the wood quality traits of logs, board recovery and board characteristics.

2 Materials and methods

2.1 Measurements on trees and harvested logs

For this study, a fast-grown *E. nitens* plantation was selected as the source for the timber material. The study site was located in southern Tasmania, Australia (at latitude 43°03' S, longitude 146°59' E) and was harvested for pulplog production in 2018, when the trees were 21 years old. Fifteen trees of merchantable form and straightness were selected for harvesting and intensive sampling. The harvesting took place during a commercial pulpwood harvesting operation, and the selected stems were felled,

delimbed, debarked and bucked in log lengths of 5.5 m each. Each stem was felled at a stump height of about 30 cm and all logs of a small end diameter of at least 185 mm were retained as sawlogs. One to four logs per tree were obtained, for a total of forty-nine harvested logs. Logs sourced from the same tree were grouped together in cutting order and each log was marked with a tree number and log position in the stem as bottom (A), second (B), third (C) and fourth (D) log to maintain identity.

To test log density, a sample from each top end of the logs was collected, sawing 2.5 cm thick discs which were wrapped in plastic and transported in a cooler to the laboratory to measure density and moisture content. Green (GD, kg/m³) and basic density (BD, kg/cm³) were measured according to AS/NZS 1080.3:2000 (Standards Australia 2000), with measurements of volume and weight of the disks being performed using the water displacement method (Smith 1954). Green density and BD of logs were calculated as an average of the GD or BD measurements of the bottom and top disks of the log. Figure 1 shows the process of selection from trees, to logs (with the disks for density measures), to boards, again with timber samples for density measures.

Logs were delivered to the mill and placed on bearers 50 cm apart for further assessments. A colouring pattern was applied to each log end to maintain traceability through the sawing process. Logs were measured at both ends for maximum and minimum diameters (large end diameters and small end diameters, mm), log length (L, m) and log sweep at midpoint-2.6 m. The log end splitting was measured on each log face and on the side surface. From the above measurements, log volume (Eq. 1), log taper (Eq. 2), log sweep (Eq. 3) and log cylindricity (Eq. 4) (Warensjö and Rune 2004) (Fig. 2) were calculated. Log

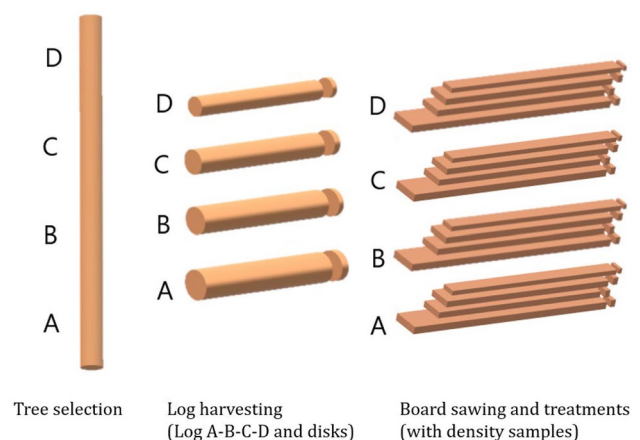


Fig. 1 Tree, log, and board processing. Trees were harvested and bucked up to four logs per tree, which were all sawn into structural boards. Log disks were cut to test for log density, and board samples were cut to test board density

Fig. 2 Examples of log characteristics: **a** log without sweep, minimal taper and no deviation from cylindricity, **b** log presenting deviation from cylindricity, **c** log presenting large taper, and **d** log presenting large sweep

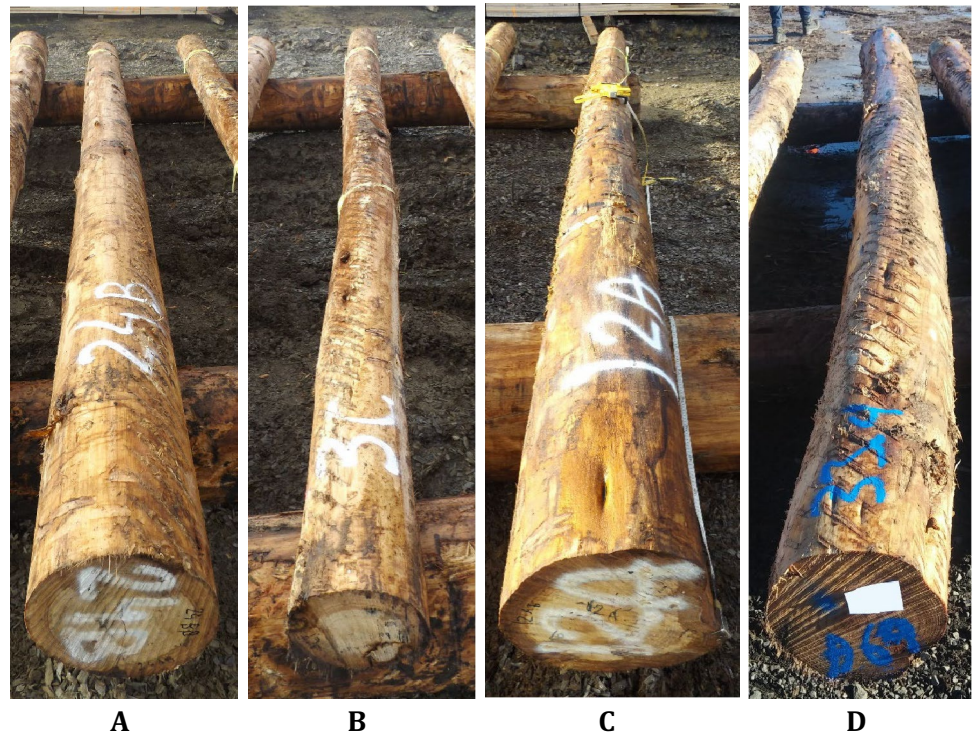
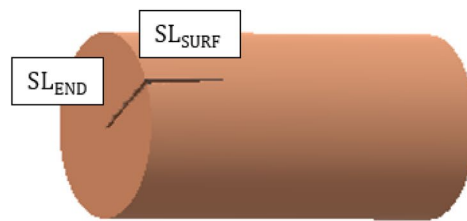


Fig. 3 Log split index recording: SL_{END} is recorded on the log face (right-hand side picture and left-hand side picture) and SL_{SURF} is recorded on the log surface



end splitting was measured at both long ends and calculated according to Eq. 5 (Yang 2005) (Fig. 3).

$$V = \left[\frac{D_1 + D_2 + D_3 + D_4}{4} \times \frac{1}{2} \right]^2 \times \pi \times L \quad (1)$$

where V is the log volume in m^3 , D_1 (larger) and D_2 (smaller) are large end diameters, in m, D_3 (larger) and D_4 (smaller) are the small end diameters, L is log length (m).

$$T = \left[\left(\frac{D_1 + D_2}{2} \right) - \left(\frac{D_3 + D_4}{2} \right) \right] / L \quad (2)$$

where T is taper, in cm/m, and D and L the already defined diameters and length.

$$Z = S/L \quad (3)$$

where Z is sweep, in cm/m, S is the maximum deviation of the centre line of the log from a straight line between the mid-points of the two ends (mm) and L is already defined.

$$C_{LOG} = \frac{1}{2} \times \left(\frac{D_2}{D_1} + \frac{D_4}{D_3} \right) \quad (4)$$

where C_{LOG} is the cylindricity of the log.

$SPLIT_{index}$ defined the split of each end, and the two log end values were then averaged per each log.

$$SPLIT_{index} = \frac{(SL_{END}^2/2) + SL_{SURF} \times SL_{END}}{R^2} \quad (5)$$

With SL_{END} being the split length on the cut end of the log, SL_{SURF} the split length on the log surface and R the mean radius of the log end.

Non-destructive techniques were employed to record the stiffness of the logs measuring the acoustic wave velocity (AWV, km/s) of logs in the field. The AWV of each log was tested with the acoustic resonance device Director HM200 (Fibre-gen, New Zealand). The hand-held tool was placed on the log end, which was then tapped with a hammer; the tapping generates a series of reverberating waves, which velocity is measured by the tool. The stiffness of the log was then calculated as MOE_{dyn} (GPa) according to Eq. 6:

$$MOE_{dyn} = GD * AWV^2 \quad (6)$$

2.2 Sawmill conversion and sawn-boards treatments

Logs were back sawn in a commercial sawmill, maximising timber recovery and retaining the sapwood. The target board dimensions were 75, 100, 125, 150 mm wide $\times$ 45 mm thick, and board length was maintained at 5.5 m without any end board docking. A total of 268 boards were obtained, block stacked, tallied and transported to the drying mill. The air-drying period lasted for fourteen months, then boards were treated under a reconditioning cycle and finally kiln-dried to a nominal moisture content (MC) of 12%. Both reconditioning and kiln drying procedures followed the current schedules used for eucalypt timber. The dried boards were square dressed to final widths of 70, 90, 120, 140, 165 mm (five boards were oversized as green), thickness of 35 mm, and average board length of 5.5 m. Boards were measured for total length, width, and thickness on five points along the length both before and after the dressing, to calculate their volume and to allow for calculation of the nominal (N_r) and dressed (N_d) recovery rate, according to Eq. 7:

$$N_{r/d} = \frac{V_{O/I}}{V_L} \quad (7)$$

where N_r or N_d represents the nominal or dressed recovery rate of the boards (%), V_O or V_I represents the volume of the boards before or after dressing (m^3), V_L is the total volume of the harvested logs (m^3). The dressed boards were transported to the engineering laboratory of the University of Tasmania, where they were manually measured and their quality visually assessed. Quality assessments were performed following AS 2082 (Standards Australia 2006), the grading standard adopted in Australia for structural boards.

Dimensional defects including spring, bow, twist, cupping, and board end splits were measured at both ends of each board (mm). The aggregate length of splits per board was used to calculate a split ratio as the surface covered

by splits over the total surface of the boards. The presence of significant checking on the boards surface was assessed, recording checks with individual length exceeding $\frac{1}{4}$ of the board's length, while the presence of checking was visually assessed and recorded on a scale from 0 (no presence of checking) to 3 (board surface severely checked). Collapse was recorded on a scale from 0 (no collapse presence) to 3 (heavy presence of collapse on the boards surface). Slope of grain was measured according to AS 1080.2 (Standards Australia 2006), to check for deviations of the grain from the surface of the boards. Down-grading defects such as the presence of rot, wane (traces of under-bark surface), bark, traces of insects and fungal decay, the presence of gum vein and resin pockets were all recorded. Debarking damage and blade damage were also checked for and recorded. Each board was inspected for features, and the total amount of knots, number of major knots (with knot diameter equal to or larger than $\frac{1}{4}$ of the width of the board), the presence and number of knotholes, knot clusters, knot groups, and knot type (alive and dead) were recorded. Clearwood, defined as wood free from defects or impermissible features, was recorded as total length of sections per board where a clearwood section was equal to or longer than 500 mm on each board. The aggregate length of clearwood per board was used to calculate a clearwood ratio, as the amount of clearwood on the surface over the total surface of the boards.

The board static modulus of elasticity ($MOE_{b,stat}$, GPa) was tested in an edge-wise four-point static bending test following AS 4063.1 (Standards Australia 2010), and calculated according to Eq. 8:

$$MOE_{b,stat} = \frac{3al^2 - 4a^3}{4bd^3 \left(\frac{\varphi_2 - \varphi_1}{F_2 - F_1} \right)} \quad (8)$$

where the thickness of the board (mm) is measured as b and the width as d , l is the span length, corresponding to 18 times the width (mm), a corresponds to 6 times the board width (mm), while F_2 and F_1 are two load measurements corresponding to 40% and 10% of the maximum load at failure point (F_{max}). The maximum displacement (mm) at the two F_2 and F_1 loads is represented by φ_2 and φ_1 , respectively. Each board was tested under bending, measuring the displacement of the mid-point of the boards with a known applied force in the linear region of the load.

One hundred boards were selected to represent equally at least one board per log and one board per width. The selection was made randomly on the number of boards available per log and width groups. Modulus of rupture (MOR, MPa) was calculated testing the boards in an edge-wise destructive bending test, following AS 4063.1 (Standards Australia 2010), and calculated according to Eq. 9:

$$MOR = \frac{3F_{max}a}{bd^2} \quad (9)$$

Density (BD) and moisture content (MC) of each board were measured from samples cut from the ends of each test board (Fig. 1), which were tested according to AS 1080.3 and AS 1080.1 (Standards Australia 2000, 2012) following Eqs. 10 and 11:

$$BD = \frac{m_1}{V} \times \frac{100}{(100 + MC)} \quad (10)$$

$$MC = \frac{m_1 - m_0}{m_0} \times 100 \quad (11)$$

where m_1 is the mass of the sample at the time of the testing (kg), V is the volume of the sample before oven-drying (m^3), m_0 is the mass of the sample after oven-drying (kg). The MC and BD of each board were calculated as an average of the samples at the bottom and top ends of each board. The $MOE_{b,stat}$ values obtained were adjusted based on the MC of each board, according to AS 2878 (Standards Australia 2017).

2.3 Statistical analysis

Statistical analyses were performed using R studio statistical software (RStudio Team 2016).

The mean, standard deviation, and value ranges were calculated for each variable on logs and boards. One-way analysis of variance (ANOVA) for linear mixed models was used to test the effect of log position on log variables (volume, taper, sweep, cylindricity, split index, density and stiffness as MOE_{dyn}) with tree as a random factor to account for non-independence of logs. Post hoc Tukey tests were conducted to compare log variables between logs (significance level 0.05). Assumptions of normality and homogeneity of variance were tested through Shapiro–Wilk’s test and graphical analysis of residuals plots. All variables met the assumptions except for sweep, and split index which were modelled through generalised linear mixed model with a *gamma* distribution function (Bates et al. 2015; Pinheiro and Bates 2000).

Potential effects of log position on selected board characteristics were investigated through ANOVA for linear and generalised linear mixed models, with tree and log as random factors to account for non-independence of boards from a log and logs sourced from the same tree. Post hoc Tukey tests were conducted to compare board characteristics between logs (significance level 0.05). The board characteristics which did not show a normal distribution of the residual were modelled through generalised linear mixed model with a *gamma* distribution function (spring, bow, split ratio,

clearwood ratio) and *Poisson* distribution function (number of alive, dead and major knots). MOE , MOR and basic density presented a normal distribution of the residuals and were modelled through linear mixed models.

To examine the relationship between log traits, board recovery and board characteristics, ANOVA was used for mixed effect models, where the fixed effects were the log variables including log position, log volume, taper, sweep, circularity, split index, basic density and MOE_{dyn} . We selected as response variables those characteristics of interest for the production of structural boards: the volume of boards per log (as recovered dressed volume), the split ratio per board, the percentage of clearwood per board, $MOE_{b,stat}$ and MOR . We included in the model random effects for board within a log ($\sim N(0, \sigma_b^2)$) and log within a tree ($\sim N(0, \sigma_L^2)$). To gauge the strength of the relationship between the log traits that displayed a significant influence on board characteristics, we used correlation analysis, through the Pearson correlation coefficient at a probability of $P < 0.05$.

3 Results

3.1 Longitudinal variation in log properties

From the selected trees 18.5 m^3 of logs were recovered. Logs differed largely in their quality traits, depending on which position they were sourced from within the tree (Table 1). There was an expected decrease in volume from bottom to top logs, with significantly ($P < 0.001$) less volume in logs located in upper positions in the stems. Other volumetric traits varied between log position as well; it was expected bottom logs to present more taper, and significantly higher ($P < 0.001$) taper values in bottom logs in comparison to second and third logs were found, with double the taper in bottom logs than second logs. Large taper values were also present in the uppermost logs, which are those holding the tree crown where the stem is slender. Although taper and volume were different among logs, no significant difference in log sweep among logs originating from different positions in the stem was found, indicating logs were similarly straight. Some differences were instead found for the cylindricity of the logs, where values close to 1 mean that the log shape resembles that of a cylinder, with small shape variations which might impact the recovery of sawn timber. Second logs were significantly more cylindrical than bottom logs ($P < 0.03$), reflecting the differences in volume and taper between logs, which modify the overall shape. Different logs also presented variable amounts of log end splits, with bottom logs having larger end splits, significantly higher than second ($P < 0.04$) and third logs ($P < 0.001$), which had half

Table 1 Log quality traits. Log class indicates log position in the stem: log A (bottom logs), B (second logs), C (third logs), D (top logs)

Log class	N	Volume (m ³)		Taper (cm/m)		Sweep (mm/m)		Log Cylindricity		Split Index		Basic density (kg/m ³)		MOE _{b,stat} (GPa)	
		Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
A	15	0.50 (0.09)a	0.37–0.74	1.08 (0.34)a	0.45–1.78	4.40 (3)a	0–9.04	0.95 (0.02)	0.91–0.98	1.52 (1.30)	a	515.4 (37.2)a	445.8–573.1	14.4 (2.09)	11.5–18
B	15	0.37 (0.07)b	0.26–0.51	0.57 (0.18)b	0.22–0.91	2.60 (3.21)	0–10	0.97 (0.01)	0.94–0.99	0.89 (0.76)	b	530.6 (37.6)a	452.1–593.9	16.8 (1.66)	13.8–20
C	15	0.28 (0.07)c	0.19–0.42	0.70 (0.18)	0.36–1.04	3.31 (3.09)	0–9.06	0.96 (0.03)	0.91–0.99	0.52 (0.32)	b	557.4 (36.9)b	475.3–622.9	16.5 (1.31)	14.2–19.0
D	4	0.27 (0.04)d	0.24–0.32	0.90 (0.19)	0.68–1.14	3.61 (2.94)	0–7.21	0.96 (0.02)	0.93–0.99	0.71 (0.72)	c	564.9 (27.3)bc	540.4–590.5	16.1 (1.28)	15.3–18.0
All logs	49	0.38 (0.12)	0.19–0.74	0.80 (0.31)	0.22–1.78	3.45 (3.08)	0–10.1	0.96 (0.02)	0.91–0.99	0.96 (0.94)		537 (40.2)	445.8–622.9	15.9 (1.94)	11.5–19.9

Letters denote significant differences ($P < 0.05$) by Tukey test

and one third of the split index value compared to bottom logs.

Significant variation in internal wood properties of logs was found originating from different parts of the stems. Basic density showed an increasing longitudinal pattern, with third and fourth logs significantly denser than bottom and second logs ($P < 0.001$). This was also reflected by an increase in modulus of elasticity, which increased significantly from bottom to second logs, leveling around 16.5 GPa on the third logs and slightly decreasing to 16.1 GPa on fourth logs, showing significantly lower values ($P < 0.001$) from both second and third logs.

3.2 Recovery rates and sawn-board properties

A total of 268 boards was recovered from the sawing of the logs, with an average of 5.5 boards per log. From bottom logs (log A) an average of 7.06 sawn boards per log was recovered, while second and third logs (B and C) respectively delivered on average 5.53 and 4.33 boards per log, and top logs an average of 3.5 boards per log. The nominal recovery rate, calculated on the number of boards before the dressing stage was 43.6%, while the dressed recovery rate was 31.4%. The average volume of dressed boards recovered per log position was calculated, finding that bottom, second, third and fourth logs have on average yielded a board recovery of 31%, 33%, 32% and 28%, respectively.

The characteristics of the sawn boards are expected to be dependent on the traits of the logs. However, in this study, no significant differences in board characteristics from logs sourced from different positions in the tree were found, except for the knot characteristics (Table 2). Boards sourced from bottom logs had significantly more dead knots than other boards, while the number of major and alive knots was significantly higher in boards from upper positions in the stem. This longitudinal pattern in variation in type and number of knots is due to the branching habit and the living conditions of the trees in the unpruned plantations, where the bottom part of the stem retains dead branches and the top presents a green crown with large branches (which will display as major knots in the boards). As found on the logs, the properties of boards varied significantly from different log positions, with a two-fold variation in basic density, from 426.1 to 778.8 kg/m³, a two-fold variation in MOE_{b,stat} from 8.26 to 18.1 GPa, and almost a six-fold variation in MOR, up to a maximum value of 110.7 MPa (Table 3). Significant differences ($P < 0.001$) were found in the density and MOE_{b,stat} of the boards originating from different stem positions, with both an increasing trend in density and stiffness towards the top of the trees. Although there were differences in density and MOE_{b,stat}, no significant differences were found in the MOR of the boards originating from different

Table 2 Board quality traits

Log class	N	Bow (mm/L)		Spring (mm/L)		Split ratio (%)		Clearwood ratio (%)		No. of alive knots		No. of dead knots		No. of major knots	
		Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
A	106	19.67 (11.7)a	0–45	8.11 (8)a	0–30	6.20 (6.44)a	0–39.8	42.9 (29.1)a	0–100	4.65 (6.75)a	0–26	6.64 (4.64)a	0–30	3.25 (4.05)a	0–17
B	83	20.30 (13.4)a	0–60	6.57 (6.78)a	0–25	5.80 (4.69)a	0–22.8	39.1 (27.7)a	0–92.9	6.59 (5.81)b	0–22	2.34 (2.34)b	0–11	6.02 (3.61)b	1–16
C	65	20.15 (14.0)a	0–70	8.62 (10.6)a	0–40	4.76 (5.11)a	0–27.6	37.4 (26.2)a	0–87.8	7.71 (5.64)b	0–25	2.02 (2.23)b	0–9	6.34 (3.33)b	2–17
D	14	21.07 (12.7)a	0–40	5.36 (7.2)a	0–20	4.92 (2.09)a	0–8.28	38.5 (26.6)a	0–88.8	8.29 (4.7)c	0–14	2.86 (2.45)b	0–6	6.79 (2.86)b	2–11
All boards	268	20.1 (12.9)	0–70	7.61 (8.35)	0–40	5.66 (5.47)	0–39.8	40.1 (27.8)	0–100	6.18 (6.23)	0–26	3.99 (4.03)	0–30	5.28 (4.06)	0–17

Bow and spring are calculated as maximum deviations on the board's length according to AS 2082. Split ratio and clearwood ratio are the percentage of board affected by board end splits and the percentage of clearwood on the board surface. Log class as explained in Table 1

MOE_{dyn} dynamic modulus of elasticity, measuring log stiffness

Letters denote significant differences ($P < 0.05$) by Tukey test

log positions. This result might be due to the number of sawn boards destructively tested for MOR, which were less than those tested for $MOE_{b,stat}$. From separate correlation analysis it was found that MOR was significantly correlated with both board's density ($r = 0.66$, $P < 0.001$) and $MOE_{b,stat}$ ($r = 0.46$, $P < 0.001$), showing that boards with high stiffness will likely also be denser and stronger.

The board characteristics were calculated according to the total number of boards per log position (Fig. 4), finding that some specific features were present, at least to a small extent, in almost all boards. All boards coming from second to top logs presented a major knot (measured according to AS 2082), while almost 70% of boards originating from bottom logs had a major knot. More than 60% of bottom boards presented severe checking, whilst the proportion of severely checked boards over the total of boards per log class decreased towards upper logs. A large percentage of boards in each log class presented surface collapse, which was present in more than 60% of boards per log class. The presence of major board end splits impacted the majority of boards in each log class, with the lowest proportion of boards with severe end splits being present in log class C, at 65%, and other log classes presenting a proportion from 70 to 85% of boards. Rot was detected in almost all log classes, although in less than 30% of boards per class. Bark and wane presence was often detected on the same board and impacted mostly those boards originating from top positions in the stem. Damage due to the processing of logs and boards was limited, with the largest being the debarking damage on boards originating from third logs. Maximum allowances for dimensional changes of the boards were evaluated according to AS 2082 (Standards Australia 2007), and only twist was detected in almost 20% of all boards in all log classes.

3.3 Log quality traits and board characteristics

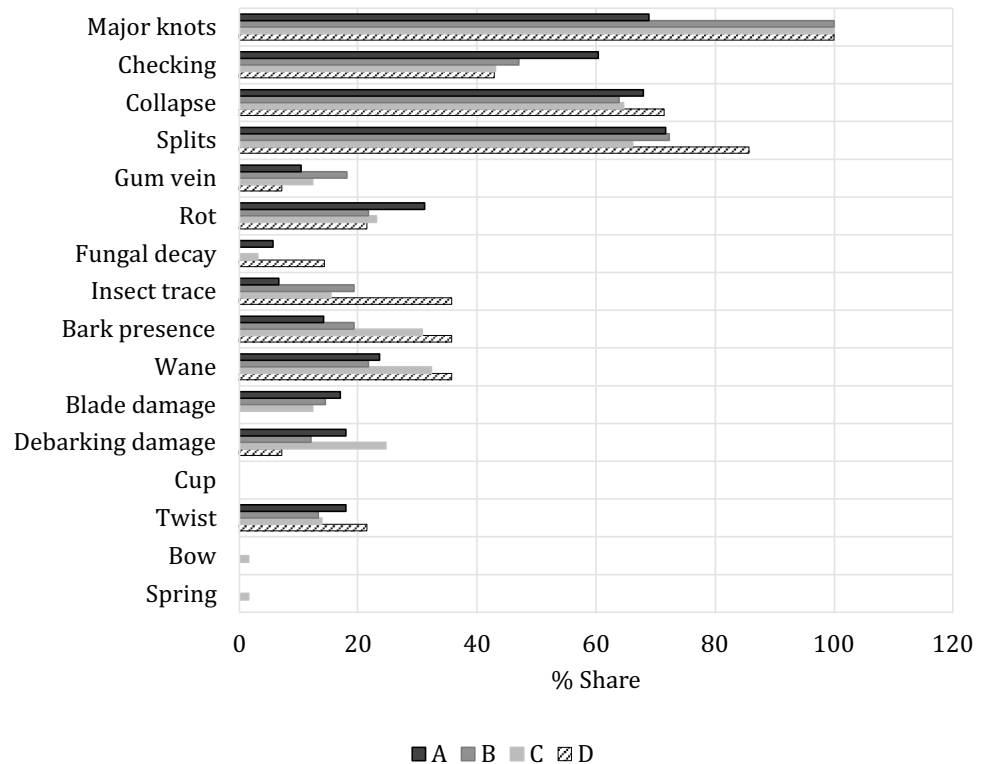
Board volume recovery was significantly impacted by log volume and log taper (Table 4), and the volume of boards recovered was positively correlated with the volume of the log. No other variables significantly influenced recovery of boards from the harvested logs. The percentage of end splits on boards was marginally influenced by the end splits on the logs. Log volume was the only log characteristic that influenced the percentage of clearwood on the boards. Log variables did not impact structural properties of the sawn boards, except $MOE_{b,stat}$ of the boards, which was highly influenced by the MOE_{dyn} of the logs.

Table 3 Board structural properties: Basic density ($n = 268$), modulus of elasticity ($MOE_{b,stat}$, $n = 268$), and modulus of rupture (MOR, $n = 100$)

Log class	N	Density (kg/m^3)		$MOE_{b,stat}$ (GPa)		MOR (MPa)	
		Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
A	106	551.3 (70.2)a	426.1–740.1	12.9 (2.25)a	8.26–17.2	63.8 (18.8)a	26.8–109.5
B	83	576.1 (56.8)b	470.4–694.6	14.2 (2.3)b	9.73–18.1	69.1 (22.2)a	20.9–101.1
C	65	615.2 (44.6)c	530.9–733.8	13.8 (2)b	10.3–17.9	70.1 (25.7)a	19.9–110.7
D	14	637.6 (51)c	596.7–778.8	14.3 (1.87)ab	11.6–17	61.1 (18)a	31.2–90.4
All boards	268	578.9 (65.9)	426.1–778.8	13.6 (2.25)	8.26–18.1	67 (21.9)	19.9–110.7

Letters denote significant differences ($P < 0.05$) by Tukey test

Fig. 4 Board characteristics per board position



4 Discussion

The quality and the quantity of timber that can be recovered from the hardwood plantation estate will inform uses on preferred markets for the resource. Understanding how plantation hardwood log traits influence the recovery of sawn boards, as well as sawn board structural traits and features, provides valuable information to inform forest growers and processors on best practices for log harvesting, grading, processing and sawmilling. In this study, significant differences in traits of logs sourced from different positions in the stems of plantation *E. nitens* were found. Despite this clear variation in traits depending on log position, the impact on board quality was only evident in density, stiffness and some board

features. Recovery of board volume was significantly influenced only by log volume and taper, while other important board traits such as end splits, amount of clearwood, and stiffness were impacted by log end splits, log volume and log modulus of elasticity, respectively.

4.1 Longitudinal variation in log properties

This is the first study of which we are aware that characterises the longitudinal variation in wood quality and log traits from harvested *E. nitens* logs and relates these traits to the characteristics of the resulting sawn boards. The differences in log quality traits found among logs indicate that logs sourced from different heights could be utilised for specific products on different sawing lines. Logs originating from the

Table 4 ANOVA results for the impacts of log characteristics on board recovery and board traits

Source of variation	Volume recovery of dressed boards		Split ratio (%)		Clearwood ratio (%)		MOE _{b,stat}		MOR	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Log	0.54	0.65	1.37	0.27	1.96	0.13	0.85	0.47	0.15	0.93
Volume	14.4	<0.001***	3.00	0.10	7.79	0.009**	1.70	0.20	0.0006	0.98
Taper	4.38	0.04*	0.52	0.48	0.18	0.67	0.62	0.43	0.68	0.41
Sweep	0.10	0.76	3.46	0.07	0.002	0.96	0.46	0.50	2.35	0.13
SI	0.33	0.57	8.38	0.007**	0.52	0.47	0.25	0.62	2018	0.14
Cylindricity	0.01	0.93	1.75	0.19	0.22	0.64	0.44	0.51	0.22	0.64
Basic density	1.21	0.29	0.05	0.82	0.05	0.83	0.05	0.82	0.43	0.52
MOE _{dyn}	0.98	0.34	2.50	0.14	3.11	0.10	10.4	0.003**	2.08	0.18

MOE_{b,stat} Static modulus of elasticity, measuring board stiffness, MOR modulus of rupture, measuring board strength, MOE_{dyn} Dynamic modulus of elasticity, measuring log stiffness

Significance levels: ***P < 0.001, **P < 0.05

bottom of the trees were significantly larger, more tapered, and had large values of sweep, but were not less cylindrical than other logs. These volumetric traits can influence the sawing recovery of timber as well as veneer recovery, if logs are to be peeled this should be taken into account prior to log processing. Mills that process larger logs for sawing and peeling might better utilise bottom logs, adapting the processing patterns to the geometry of the log, which can be scanned through log-scanners to optimise the cutting pattern (Oja et al. 2003, 2004; Rinnhofer et al. 2003). Smaller logs require sawing strategies, which would optimise the timber recovery and can adapt the pattern to the variable log geometry traits. Traditional sawing methods often fail to accommodate the small dimensions of the logs (Innes et al. 2008; Washusen 2013; Washusen et al. 2009) and appropriate sawing strategies need to be implemented to account for the characteristics of fast-grown eucalypt logs.

All logs recovered in this study showed end splitting, which was larger for bottom logs and significantly different among log positions, differing from what was previously reported for this species (Vega et al. 2016; Valencia et al. 2011). These previous studies demonstrated that upper logs presented more end splits than bottom logs. The felling procedure (manual harvesting versus machine-felling through harvesters) as well as silvicultural treatments might have impacted the development of log end splits. Moreover, the present study accounted for more logs up the stem (up to approximately 25 m height), while previous studies focused only on the first part (5.7 m) of the stem. The present results show that to gain a full appreciation of longitudinal variation in wood quality traits and features, it is important to source logs from the full height of the stem.

Density and stiffness (modulus of elasticity, MOE_{dyn}) are traits of great importance for structural products in buildings and construction components including mass timber. In this

study, higher values of both properties were found in upper positions in the stem, a finding consistent with previous research (Purnell 1988; Raymond and Muneri 2001; Shelbourne et al. 2002). The longitudinal variation in stiffness is mostly due to a combination of the effects of wood density and the microfibril angle in wood (Yang and Evans 2003), which firstly decreases and then increases towards the top of *Eucalyptus* stems (Evans, et al. 2000). The combination of increased stiffness as well as density indicates that logs from upper positions in the stems would deliver timber of higher structural properties. Traditionally, bottom logs are preferred for sawing as they deliver the most volume (personal communication), with other logs are destined for other uses such as pulp. This study shows instead that if stiffer timber is sought, the best choice for sawlogs sourcing would lie in other (upper) logs.

4.2 Recovery rates and sawn-board properties

Significant variation in the recovery of board volume from logs originating from different positions was expected, as logs of different shapes and volumetric characteristics have been sawn. The recovery rates obtained in this study are higher than those previously recorded on similar resources (Derikvand et al. 2018a, b) due to both the sawing pattern and the use of all logs from the tree, supporting the hypothesis of sourcing logs from all heights up the stems for sawing, rather than limiting the use to bottom logs. Moreover, although the volume recovery from second logs was the highest (33%) it was not different from that of other logs, showing that, proportionally, smaller logs can contribute a similar recovery to larger logs.

No significant variation was found in sawn board characteristics due to log position in the stem. Dimensional distortions including bow and spring, which would lead

to dimensional instability of the boards, were not different among logs, suggesting that control of variation of these traits is from sources other than log position, for example from release of stress during sawing (Washusen 2013). Important appearance traits, such as the presence of features, were instead different in boards sourced from different heights in the stem, as well as the structural traits, stiffness and density. The increased number of dead knots on boards from bottom logs, and alive knots on boards from top logs, are most likely related to the branching habit of *Eucalyptus* trees, which retain dead branches on the bottom part of the stem, and when the timber is sawn these lead to the trace of the branch as a dead and loose knot (Jacobs 1955).

While there were differences in knot type and number of knots per log position, it was found that the vast majority of boards presented at least one major knot. In this study we followed the Visual-Stress Grading (VSG) system for structural timber according to the Australian Standard (Standards Australia 2007), in which the allowance for major knots for the highest board grade are for knots equal or smaller than $\frac{1}{4}$ the width of the board. Boards which present features and knots larger than this size, are relegated to lower grades, following the traditional rationale in which large knots decrease the overall board stiffness. The same logic applies to checking, which is typical of several *Eucalyptus* species (Elaieb et al. 2019) and is generally managed through application of appropriate drying schedules and pre-steaming processes (Yang and Liu 2018). Although the present study has applied long air drying and a reconditioning treatment to reduce checking and collapse, overall checking still impacted more than 40% of boards in each log class on the dressed material. For fast-grown eucalypt material, knot and checking limitations present in the traditional VSG are too restrictive, leading to down-grading of structural boards which could instead reach stiffness values as high as commercial structural grades (Balasso et al. 2021; Derikvand et al. 2018a). Moreover, standards based on visual grading of boards do not account for the final use of the material, and in the case of mass timber the importance of features and checking is much lower than for single board elements used as such, as those can be handled in the lamination of the mass timber structure (Derikvand et al. 2019a; Wessels et al. 2020).

As expected from the marked longitudinal increase in density and stiffness of the logs, larger stiffness and density values were found in boards originating from logs from upper positions. The significant differences found among boards from different logs in density and stiffness were not shared for timber strength, measured as modulus of rupture, which did not show any pattern along the stem. This leads to the conclusion that upper logs will deliver stiffer and denser sawn boards. However, board strength will be variable regardless of the position in the log and stem from which boards are sourced from.

4.3 Log quality traits and board characteristics

The ability to predict board appearance and features from the characteristics of the logs would be highly advantageous for log processors who seek to maximise their revenue from milling logs. Moreover, a clearer understanding of which log characteristics are impacting sawn timber volume and value could support the creation of log grading standards, which are reflective of the nature of fast-grown eucalypt timber. We considered characteristics, which are impacting both board volume and value recovery and found moderate associations with only a few log traits. Volume of the log was a good predictor of amount of boards recovered, as well as log taper, but other log geometrical traits did not display any influence on board characteristics. Large numbers of splits in the ends of all boards were found, which impacted the surface of the sawn timber and the overall recovery of clearwood. The amount of end splits on the boards can be predicted from the splits present on the ends of the logs, which in this study were larger on bottom logs. Accounting for log splits prior to log processing can improve the amount of sawn timber recovered and limiting the appearance of splits on log ends would be preferable. Previous research has found some effects on log end splits from storage time of logs, but no improvement of splitting due to log steaming treatments (Vega et al. 2016) and more studies are needed in this area.

The visual characteristics of timber are highly relevant for appearance products, in which the amount of clearwood on the boards determines the quality grade of the material. It was found that the only log characteristic which impacted clearwood on boards was log volume, mostly due to the fact that larger logs would deliver more timber and larger sections of wood free from features. If recovery of sawn boards with substantial amount of clearwood is of interest, as is the case for appearance timber, bottom logs with a large volume should be segregated and allocated for this use. This observation is important for log grading standards for appearance products. However, for standards dealing with structural products, where stiff timber is required, the most important log characteristic would be log stiffness, which might be considered in future log grading standards for structural timber. Log stiffness and log position are correlated, which explains why log stiffness was detected as the only source of variation of stiffness of boards. If log stiffness information was not available prior to milling logs, log position could be used instead, considering the consistent finding of stiffer logs and stiffer boards originating from upper positions in the stems.

5 Conclusion

Log quality traits are important variables that can be used to batch harvested logs into quality classes, or grades, following appropriate grading standards. Logs originating from a fast-grown eucalypt resource need appropriate grading, which would take into account log characteristics and the impact of those characteristics on the sawn timber. Significant differences were found in almost all log traits, including volume, taper, log end splits, log density and stiffness, which differ in logs originating from different positions in the stems. However, the impact of those characteristics on board volume and value recovery was limited, and only log volume, taper, log end splits were important features for board traits as overall volume recovery, board end splits and amount of clearwood per board. Board structural properties are controlled by other factors, and an influence of log stiffness and log position was consistently found in determining board stiffness. The traits highlighted in this research can be employed to develop an updated grading standard for fast-grown eucalypt logs to serve different markets, including mass timber and engineering wood products.

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