

# Factors affecting log traits and green rotary-peeled veneer recovery from temperate eucalypt plantations

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## Abstract

• **Key message** High levels of percentage green veneer recovery can be obtained from temperate eucalypt plantations. Recovery traits are affected by site and log position in the stem. Of the post-felling log traits studied, out-of-roundness was the best predictor of green recovery.

• **Context** *Eucalyptus globulus* and *Eucalyptus nitens* are widely planted in temperate regions of the globe but few studies of rotary peeling have been documented.

• **Aims** This study aims to examine differences among sites and log positions in post-felling log traits and green veneer recovery traits and determine the extent to which log traits explain variation in recovery traits.

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**Contribution of the co-authors** All authors undertook writing/editing the manuscript and all, except Brad Potts, were involved in data collection. Matthew Hamilton oversaw the selection, felling and transport of logs, undertook statistical analyses and wrote the first draft of the manuscript. Robert McGavin and Henri Baillères oversaw the peeling of logs.

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• **Methods** Log traits and green rotary-peeled veneer recovery traits from six temperate eucalypt plantations were studied. Selected plantations encompassed different age, site productivity, silvicultural and species classes in south-eastern Australia. Differences in log and recovery traits among sites and between lower and upper logs were examined, as was the extent to which log traits explained variation in recovery traits.

• **Results** Differences among sites for percentage recovered green veneer were non-significant, despite significant differences for peelable billet volume, roundup loss, residual core diameter and all post-felling log traits: small end diameter, sweep, taper, out-of-roundness, end splitting and dynamic modulus of elasticity ( $MOE_{dyn}$ ). The lower log exhibited more sweep, taper and out-of-roundness but lower  $MOE_{dyn}$  and less recovered green veneer. Out-of-roundness was the best predictor of recovery traits ( $R^2 = 13\text{--}21\%$ ,  $P < 0.001$ ).

• **Conclusion** Recovered green veneer was high across all sites and log positions (78 % overall).

**Keywords** *Eucalyptus globulus* · *Eucalyptus nitens* · Site effect · Log position · Log characteristics

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## 1 Introduction

*Eucalyptus globulus* and *Eucalyptus nitens* are widely planted in Australia, Chile, Spain, Portugal and South Africa and are primarily managed as unthinned and unpruned stands for pulpwood. However, sizable areas of plantation have been thinned and pruned, targeting clearwood (i.e. knot-free) logs for the production of decorative sawn timber and face veneer. For example, in Tasmania, Australia, approximately 26 000 ha of predominantly *E. nitens* plantation is managed under such regimes (Wood et al. 2009). *E. globulus* is generally regarded as superior to *E. nitens* in terms of its kraft-pulping properties (Downes et al. 2006; Kibblewhite et al. 2000), strength, stiffness and hardness (McKinley et al. 2002; Potts et al. 2011) but *E. nitens* is more cold tolerant (Wardlaw 2011) and is less susceptible to *Mycosphaerella* leaf disease (Mohammed et al. 2003).

In the Australian context, the potential of the standing hardwood plantation resource as a feedstock for processes and products other than pulpwood is not well understood, as the bulk of the hardwood plantation estate was established relatively recently. This is exemplified by a dearth of studies examining the potential for the production of rotary-peeled veneer from either *E. globulus* or *E. nitens* (Blakemore et al. 2010; Blackburn et al. 2012; Farrell et al. 2011; McGavin et al. 2014). In several Asian countries, small-diameter unthinned and unpruned eucalypt logs are rotary peeled, generally by small-scale processors in regions with low labour costs (McGavin et al. 2014; Arnold et al. 2013; Luo et al. 2013). Alternative uses for the *E. globulus* and *E. nitens* plantation resource are of interest to growers and processors as a means of increasing grower returns and establishing profitable processing industries (Washusen et al. 2009; Washusen 2011; McGavin et al. 2014).

Although the value of veneer products is ultimately determined by grade recovery and utility after drying, maximising the recovery of green veneer from billets is a fundamentally important consideration in maximising the profitability of rotary peeling operations (Shi and Walker 2006). Green veneer recovery can be expressed as the recovered percentage of the green billet volume, prior to billet roundup and peeling. Billet roundup is the first step in rotary peeling, where irregularly shaped billets are machined to a cylindrical peeler block. No useable veneer is recovered during roundup. Once billets are cylindrical, they are peeled to recover green veneer down to a residual core (i.e. the peelable volume of a log is represented by a hollow cylinder). Accordingly, green recovery is maximised when roundup loss and residual core diameter are minimised. Log characteristics affecting roundup loss and residual core diameter are different. Post-felling log traits such as small end diameter under bark, sweep, taper, and out-of-roundness might be expected to impact on roundup loss (McGavin et al. 2014; Luo et al. 2013), and factors affecting

wood integrity and strength, such as log end splitting and wood decay (incipient or advanced), are likely to directly affect residual core diameter.

The specific objectives of this study were to determine the following:

- If there are differences among sites in post-felling log traits, including small end diameter under bark, sweep, taper, out-of-roundness, end splitting and dynamic modulus of elasticity
- If there are differences among sites in green veneer recovery traits, including peelable billet volume, recovered green veneer, roundup loss and residual core diameter
- Whether differences among sites are stable regardless of billet position
- The extent to which post-felling log traits explain variation in recovery traits

Appropriately matching plantation species, silviculture and environment to processes and products has the potential to unlock previously unidentified value in the standing plantation resource. The findings of this study will inform decisions regarding standing resource utilisation, plantation research and ultimately species selection, site selection, forest management and product use optimisation.

## 2 Materials and methods

Trees for the study were sourced from six temperate eucalypt plantations located in south-eastern Australia near Strathblane, Geeveston and Florentine Valley in Tasmania and Deans Marsh, Orford and Mumbannar in Victoria. These plantations were selected to represent a range of environments and silvicultural regimes under which temperate eucalypt plantations are grown. Florentine Valley (*E. nitens*), Orford (*E. globulus*) and Mambannar (*E. globulus*) represented harvest-age pulpwood stands, and Strathblane (*E. nitens*), Geeveston (*E. nitens*) and Deans Marsh (*E. globulus*) represented thinned and pruned stands, although none had yet reached their notional harvest age of 25–30 years. The age at which individual plantations are commercially harvested is a function of growth rates and economic parameters.

Basal area plots were established in each plantation from which study trees for rotary peeling were selected at random. To avoid the selection of severely suppressed trees and to meet the splindleless lathe diameter requirements, trees at most sites that were less than 220 or greater than 390 mm in diameter at breast height over bark (DBHOB; 1.3 m) were excluded. Trees with ramicorns, double leaders, major branches or visible external injuries that would have precluded peeling were also excluded. At the Geeveston site, where average tree diameter was greatest, the maximum diameter criterion for

the spindleless lathe was relaxed. The number of trees sampled, location, species, silviculture, environmental characteristics, genetic origins, year of planting and felling method for each site are detailed in Online Resource 1.

Two 2-m logs were cut from each tree on the same day as felling—one from 0.5 to 2.5 m and the other from 3.7 to 5.7 m from the base of each stem. Logs were transported to one of two log yards—Geeveston (Tasmania) or Hamilton (Victoria)—for debarking, measurement and loading into a shipping container for transport to the Salisbury Timber Research Facility in Brisbane.

Large-end-diameter under bark (LEDUB) and small-end-diameter under bark (SEDUB) were assessed on each log using a diameter tape. Log taper was estimated as the difference between LEDUB and SEDUB divided by the log length. In addition, the minimum and maximum SEDUB and LEDUB were measured through the centre of the log (i.e. ignoring the position of the pith) using a steel rule and out-of-roundness estimated for each log end as the difference between the minimum and maximum diameter divided by the average of the minimum and maximum diameter (Warensjo and Rune 2004). Log end estimates of out-of-roundness were then averaged for each log. Log sweep was measured as the maximum deviation from a taut string, bridging the log ends, to the log surface. Log end splitting was assessed approximately 24 h after cross cutting according to the ‘Split Index 2’ method outlined in Yang (2005):

$$\text{Individual split index} = \frac{\frac{SL_{\text{END}}^2}{2} + SL_{\text{SURFACE}} * SL_{\text{END}}}{R^2}$$

where  $SL_{\text{END}}$  is the split length on the log end,  $SL_{\text{SURFACE}}$  is the split length on the log surface and  $R$  is the mean radius under bark of the log end. The Log Split Index was calculated as the sum of all individual split indices for each log.

Logs were kept damp prior to transport to the Salisbury Timber Research Facility. Upon arrival, longitudinal acoustic vibration measurements were captured on all logs using the CIRAD Bing® device to allow estimation of dynamic modulus of elasticity (Brancheriau and Bailleres 2002). Two-metre logs were then docked to produce 1.3-m peeler billets. At the time of docking, cross-cuts were positioned to minimise end splitting in peeler billets (i.e. the position of cross cuts varied among billets) and the expression of splitting in veneer sheets. After docking, SEDUB and LEDUB were reassessed using a diameter tape and billet volume was estimated according to Smalian’s formula—the billet length (1.3 m) multiplied by the average of the areas of the two billet ends.

Billet roundup and peeling was undertaken using an OMECO spindleless veneer lathe model TR4 (McGavin et al. 2014). The time between felling and peeling ranged from 14 to 30 days. Twelve billets from the Geeveston site

were too large to be peeled with the spindleless lathe (>400 mm LEDUB). These logs were rounded and/or partially peeled using a conventional spindled lathe prior to docking and peeling using the same procedure outlined for other billets.

Billet diameters were measured with a tape after roundup and prior to the peeling of a veneer ribbon with a targeted thickness of 2.8 mm. The width of the veneer ribbon (perpendicular to the grain) and the diameter of the residual billet core were measured. The mean veneer thickness for each billet was calculated from green veneer thickness measured using a dial thickness gauge with a nominal precision of 0.01 mm. Thickness was assessed at three points along the length (ends and midpoint) of 150-mm-wide samples clipped from the veneer ribbon between full veneer sheets which were nominally 1400 mm wide (McGavin et al. 2014).

‘Peelable billet volume’ was estimated as the difference between rounded up billet volume and residual core volume, both of which were estimated, assuming they were cylinders, from measured diameters and billet length (Online Resource 2). Recovered green veneer volume was estimated for each billet as the product of billet mean green veneer thickness, ribbon width and billet length. Roundup loss was calculated as the difference between total billet volume and rounded up billet volume. Peelable billet volume, recovered green veneer volume and roundup loss were expressed as a percentage of total billet volume for analyses.

The minimum residual core diameter was 49 mm and the maximum 123 mm but the majority of billets, 139 of 201 peeled, had a core diameter within  $\pm 1$  mm of 50 mm. Accordingly, logs were partitioned into one of two categories: those that were deemed to have been peeled to the targeted residual core diameter (i.e.  $50 \pm 1$  mm; ‘target-sized’) and those that were not (i.e.  $>51$  mm; ‘over-sized’). Possible causes of oversized residual cores include the presence of splits, decay and concentration of strength reducing defects, such as knots, in billets.

## 2.1 Statistical analyses

To examine the effects of site and log position on post-felling log traits (SEDUB, sweep, taper, out-of-roundness, end splitting and dynamic modulus of elasticity ( $MOE_{\text{dyn}}$ )) and the three green recovery traits expressed as a percentage of log volume (peelable billet volume, recovered green veneer volume and roundup loss), the SAS™ Proc Mixed procedure for repeated measures (Wolfinger and Chang 1995) was used. A fixed-effect model was fitted including site, log position and their interaction as explanatory variables. As trees represented independent experimental units and measurements on billets represented repeated measures of traits on these independent experimental units, tree was fitted as the subject effect and an unstructured within-subject variance covariance matrix was

assumed. Data were transformed in cases where residuals exhibited heteroscedasticity and/or deviated from the assumption of normality (Online Resource 2). The green recovery trait of residual core diameter was analysed as a binary variable, fitting the same model terms as for the other traits, with a logit link function using the SAS<sup>TM</sup> Proc Glimmix procedure, as residuals could not be normalised using other forms of transformation.

To examine the extent to which post-felling log traits explained variation across sites and log positions, regression analyses were undertaken fitting recovery traits, except residual core diameter, as response variables and log traits as explanatory variables. Only post-felling log traits for which there was an a priori hypothesis that they affect the recovery trait were included as explanatory variables (Table 1). Univariate and multiple regression analyses were undertaken using the SAS<sup>TM</sup> Proc Reg procedure. Individual simple linear regression analyses were undertaken for all combinations of explanatory variable and response variable. Furthermore, regression analyses were repeated using standardised log and recovery data—where data for each log and recovery trait were standardised to have a mean of zero and standard deviation of one within each combination of site and log position. Regression analyses based on standardised data were used to gauge the extent to which log characteristics explained variation in recovery traits within a site and log position cohort, in contrast to analyses based on the non-standardised data which did not account for the origin of logs.

Regression analyses were not undertaken for the binary recovery trait of residual core diameter. Instead, the effect of the post-felling log traits SEDUB, end splitting and MOE<sub>dyn</sub> on core diameter was gauged by testing the difference in the mean of target-sized and over-sized cores for these traits with two-way *t* tests.

### 3 Results

#### 3.1 Differences among sites and log positions

Significant differences were observed among plantation sites in all post-felling log traits (Table 2)—SEDUB was greatest at

**Table 1** Response and explanatory variables included in regression analyses

Response variable (recovery trait)	Explanatory variables (log traits)
Peelable billet volume (%)	SEDUB, sweep, taper, out-of-roundness, end splitting and MOE <sub>dyn</sub>
Recovered green veneer (%)	SEDUB, sweep, taper, out-of-roundness, end splitting and MOE <sub>dyn</sub>
Roundup loss (%)	SEDUB, sweep, taper and out-of-roundness

Geeveston, sweep greatest at Orford, taper and out-of-roundness greatest at Deans Marsh, end splitting greatest at Geeveston and Orford and MOE<sub>dyn</sub> greatest at Orford (Fig. 1). There were significant differences between the upper and lower logs for all log traits except end splitting (Table 2, Fig. 1e). Across the sites, the lower log exhibited the greatest SEDUB, taper, out-of-roundness and sweep but the upper log had greater MOE<sub>dyn</sub> (Table 2).

A significant ( $P < 0.05$ ) site by log interaction effect was evident in SEDUB, out-of-roundness, end splitting and MOE<sub>dyn</sub> (Table 2). However, the *F* ratios associated with the main effects of site and log position were, for the most part, substantially greater than those for the interaction in these traits, and the ranking of the lower and upper log was generally consistent across sites (Fig. 1a, d–f). Exceptions to these general observations were the *F* ratio for the effect of log position on end splitting, which was exceptionally low and non-significant (Table 2; Fig. 1e) and the ranking of log positions for out-of-roundness at Deans Marsh (Fig. 1d). There was a greater difference between the upper and lower log for out-of-roundness (Fig. 1d) at *E. nitens* sites than there was at *E. globulus* sites.

For the recovery traits, a significant difference between the upper and lower log was present in all but residual core diameter class (Table 2). Across the sites, the upper log had the greatest peelable billet volume (%) and recovered green veneer (%), and the lower log exhibited the greatest roundup loss (%). There was no significant difference among sites in recovered volume of green veneer but there were significant differences among sites in peelable billet volume, roundup loss and residual core diameter. No significant interactions between site and log position were evident for the recovery traits.

#### 3.2 Post-felling log traits as predictors of recovery

Across sites and log positions (i.e. using non-standardised data), simple linear regression analyses indicated that both taper and out-of-roundness significantly explained variation in peelable billet volume, recovered green veneer and roundup loss (Table 3). Sweep also significantly explained variation in peelable billet volume and roundup loss. Increases in sweep, taper and out-of-roundness were associated with decreased peelable billet volume and recovered green volume and increased roundup losses. Between 13.0 and 20.8 % of recovery traits was explained by out-of-roundness alone. Furthermore, multiple regression analyses revealed that out-of-roundness and sweep together explained 23.5 % of variation in peelable billet volume, 13.5 % in recovered green veneer and 26.8 % in roundup loss.

**Table 2** Least-square mean with 95 % confidence interval (back-transformed, where necessary), and *F* ratio of site, log position and site-by-log-position interaction effects on log and recovery traits

	Least-square mean (95 % CI)	Site	Log position	Site by log position
<b>Log traits</b>				
SEDUB (mm) <sup>a</sup>	272 (265–280)	19.0***	605.0***	7.4**
Sweep (mm) <sup>a</sup>	14.1 (13.0–15.4)	5.5***	114.9***	1.6ns
Taper (mm m <sup>-1</sup> ) <sup>a</sup>	9.1 (8.4–10.0)	3.5**	378.6***	2.1ns
Out-of-roundness	9.00 (8.45–9.54)	5.5***	28.7***	4.4**
End splitting <sup>a</sup>	3.15 (2.73–3.61)	9.9***	0.1ns	3.0*
MOE <sub>dyn</sub> (MPa)	15,264 (14,922–15,606)	12.6***	178.6***	5.7***
<b>Recovery traits</b>				
Peelable billet volume (%)	77.2 (76.3–78.1)	3.5**	16.4***	1.8ns
Recovered green veneer (%)	77.6 (74.9–80.3)	0.2ns	8.2**	0.7ns
Roundup loss (%)	18.5 (17.7–19.3)	3.2*	24.1***	2.1ns
Core diameter (binary: target-size=0, over-sized=1)	0.857 (0.525–1.19)	3.55**	1.19ns	0.5ns

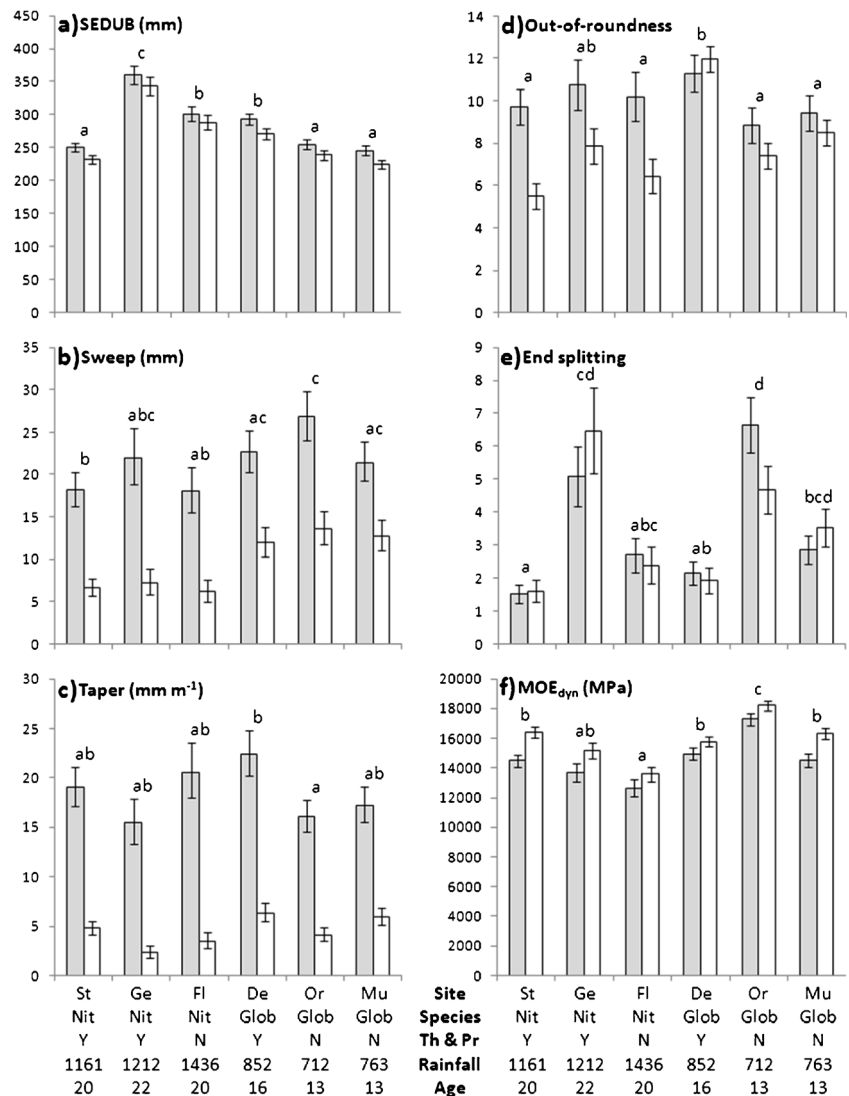
ns non-significant

\* *P* < 0.05; \*\* *P* < 0.01;

\*\*\* *P* < 0.001

<sup>a</sup> Log<sub>10</sub>(*x*+1)-transformed

**Fig. 1** Site by log position least-square means and standard errors for log traits (back-transformed, where necessary). The lower log is shown in grey and the upper log in white. The species (*Eucalyptus nitens*, *Nit*, or *E. globulus*, *Glob*), silvicultural regime (thinned and pruned, *Th & Pr*), average annual rainfall and age at felling (years) are shown for each site (Strathblane, *St*; Geeveston, *Ge*; Florentine, *Fl*; Deans Marsh, *De*; Orford, *Or* and Mumbannar, *Mu*) at the bottom of the panel. *Y* axis labels are given in the graph titles. Sites with common letters were not significantly different at *P*<0.05 following a Tukey-Kramer adjustment for multiple comparisons



**Table 3** Simple linear regression parameter estimates based on non-standardised data.

Explanatory variable (log trait)	Response variable (recovery trait)								
	Peelable billet volume (%)			Recovered green veneer (%)			Roundup loss (%)		
	Intercept	Slope	R <sup>2</sup> (%)	Intercept	Slope	R <sup>2</sup> (%)	Intercept	Slope	R <sup>2</sup> (%)
SEDUB (mm) <sup>a</sup>	68.4 (14.01)	3.53 (5.784)ns	0.2	80.0 (15.18)	-1.58 (6.261)ns	0.0	-2.4 (12.60)	8.66 (5.196)ns	1.4
Sweep (mm) <sup>a</sup>	85.7 (1.77)	-7.38 (1.438)***	11.7	81.0 (2.05)	-4.05 (1.669)ns	2.9	10.0 (1.62)	7.23 (1.319)***	13.1
Taper (mm m <sup>-1</sup> ) <sup>a</sup>	81.2 (1.35)	-4.16 (1.252)**	5.3	80.0 (1.47)	-3.76 (1.366)*	3.7	13.9 (1.20)	4.65 (1.116)***	8.0
Out-of-roundness	83.4 (1.06)	-0.72 (0.109)***	18.1	82.3 (1.20)	-0.68 (0.124)***	13.0	12.2 (0.96)	0.71 (0.099)***	20.8
End splitting <sup>a</sup>	77.1 (1.03)	-0.28 (1.539)ns	0.0	75.5 (1.14)	1.29 (1.703)ns	0.3	-	-	-
MOE <sub>dyn</sub> (KPa)	78.4 (3.11)	-0.10 (0.198)ns	0.1	74.8 (3.44)	0.09 (0.219)ns	0.1	-	-	-

Standard errors are enclosed in parentheses and Bonferroni corrected significance level of the slopes from zero are shown, along with the coefficient of determination ( $R^2$ ) expressed as a percentage. Dashes indicate parameters that were not estimated as there was no a priori expectation that the explanatory variable should explain variation in the response variable

ns non-significant

\* $P < 0.05$ ; \*\* $P < 0.01$ ; \*\*\* $P < 0.001$  after Bonferroni correction

<sup>a</sup>  $\text{Log}_{10}(x+1)$ -transformed

Within sites and log positions (i.e. using standardised data), only out-of-roundness explained significant variation in peelable billet volume, recovered green veneer and roundup loss ( $P < 0.001$ ). The amount of variation in recovery traits explained by out-of-roundness within sites and log positions was less than that explained across sites and log positions ( $R^2 = 10.7\%$  for peelable billet volume,  $9.8\%$  for recovered green veneer and  $10.2\%$  for roundup loss).

A significant difference between the mean SEDUB of log with a target-sized residual core and logs with an over-sized residual core was observed ( $P = 0.012$ ), with over-sized logs having a greater SEDUB. No significant difference between means was evident for end splitting or MOE<sub>dyn</sub>.

## 4 Discussion

### 4.1 Post-felling log traits

The selected sites encompassed a range of environments, management regimes, harvest ages, species (*E. globulus* and *E. nitens*) and other factors (Online Resource 1). Any one of, or an interaction among, these factors could explain differences in log and recovery traits observed among sites. Appropriately designed and replicated trials are required to verify the cause of differences in log and recovery traits observed among sites in the current study. Clear difference among sites in SEDUB (Fig. 1a, Table 2) reflected these differences in site characteristics. Of the log traits examined, SEDUB is the most easily manipulated through plantation genetics, site selection, management, harvest age or post-harvest segregation. In the

current study, trees were selected at random, within size and quality constraints, at each site. However, in commercial operations, trees and logs can be segregated post-felling for different markets. The ranking of sites was stable, regardless of log position, indicating that the significant site by log position interaction effect for SEDUB was primarily driven by differences in scale among log positions and/or sites.

The observation that *E. globulus* sites exhibited greater sweep than the *E. nitens* sites is in keeping with anecdotal observations by forest managers and researchers (Potts et al. 2011). *E. nitens* is generally regarded as having straight stems, whereas *E. globulus* tends to exhibit sinuosity in stem form (Blackburn et al. 2013).

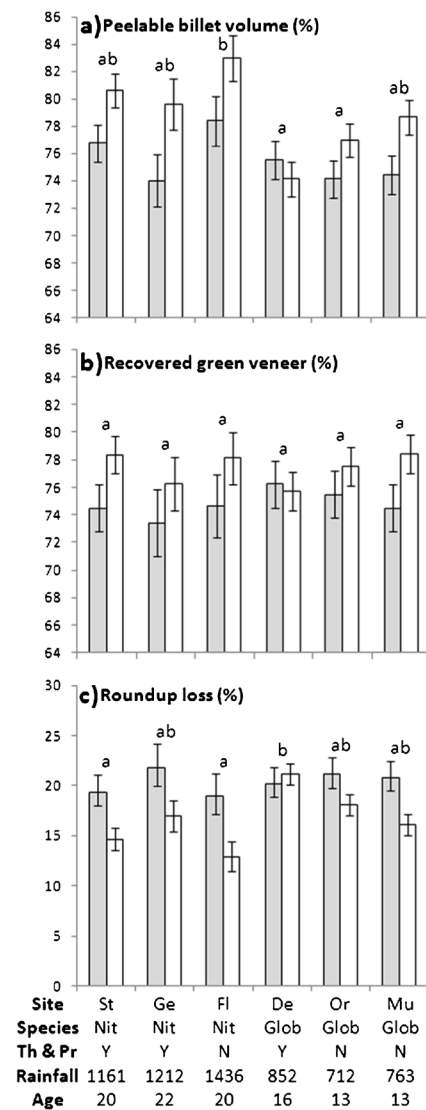
It is possible that the significant difference observed in taper between the Deans Marsh and Orford sites was a result of thinning at Deans Marsh. Thinning tends to disproportionately increase diameter relative to height (Beadle et al. 2011). Extreme butt sweep was not evident at any of the sites at the time of felling and the greater level of sweep and taper observed in the lower log was most likely due to buttressing, despite the removal of the lower 0.5 m of the stem.

Debarking at the Deans Marsh site revealed substantial bumps on the surface of logs, which was reflected in the high degree of out-of-roundness at this site. It is likely that these bumps were the result of pruning and subsequent slow growth. After final pruning in 2003, the Deans Marsh site experienced a series of below-average rainfall years (665 mm in 2004, 709 mm in 2005, 474 mm in 2006 recorded at the site) which almost certainly impacted on growth and the rate and process of branch occlusion of large branch stubs. At the time of roundup, the bumps were confirmed to be associated with occluded knots. Observations at peeling also indicated that some pruned branches were beyond the recommended

size for pruning (Pinkard et al. 2004) and many exhibited necrosis and decay. Such deformities were not prevalent at either of the *E. nitens* pruned sites, Strathblane and Geeveston. These factors are likely to explain the atypical results from the Deans Marsh site for out-of-roundness and other log and recovery traits (Figs. 1 and 2).

The most noteworthy difference between sites in end splitting was that between Strathblane and Geeveston. Both Strathblane and Geeveston were *E. nitens*, managed under similar thinning and pruning regimes and harvested at a similar age. However, the Geeveston site clearly exhibited a greater level of end splitting, possibly due to the relatively late and heavy thinning performed at this site and subsequent expression of high growth stresses, low taper, rapid growth and large diameters (Okuyama et al. 2004; Beadle et al. 2011; Kubler 1988). Geeveston was also a far more productive site than Strathblane, which was reflected in growth rate and the size of logs extracted from the site. The difference in end splitting in the lower log between Orford and Mumbannar was also noteworthy. Both of these sites were *E. globulus*, managed under similar pulpwood silvicultural regimes, harvested at a similar age and yielded logs of similar diameter. Orford was the only site at which trees were felled and debarked using a machine (Online Resource 1) and it is possible that, in this study, machine harvesting exacerbated splitting despite appearing to be more gentle and controlled. The relationships among silviculture, site productivity, harvesting method and splitting and the implications for *E. globulus* and *E. nitens* plantation management and processing require further investigation.

Modulus of elasticity is known to increase with cambial and apical age and, accordingly, log height in eucalypts (Medhurst et al. 2012), which was reflected in the findings of this study. Of the *E. nitens* sites, the thinned and pruned stands exhibited greater  $MOE_{dyn}$  than the Florentine site. The Strathblane and Florentine sites were both of a similar age and it is possible that this difference in  $MOE_{dyn}$  was caused by silvicultural differences (Beadle et al. 2011). Species differences across these sites were confounded with harvest age and silvicultural differences and the finding that older thinned and pruned *E. nitens* sites have comparable  $MOE_{dyn}$  to *E. globulus* sites, which is generally regarded as having superior stiffness to *E. nitens*, is encouraging for *E. nitens* growers. By delaying the harvest of their resource, they could potentially meet the requirements of structural products for which the species was previously considered unsuitable (Farrell et al. 2011). Of the *E. globulus* sites, Deans Marsh was thinned and pruned and yet had a lower  $MOE_{dyn}$  than the younger Orford site, which likely reflects the high levels of decay observed in logs from the Deans Marsh site and, potentially, a higher proportion of low-MOE corewood resulting from early thinning. However, the difference in  $MOE_{dyn}$  between Orford and Mumbannar, which were both *E. globulus*, unthinned and unpruned,



**Fig. 2** Site by log position least-square means and standard errors for peelable billet volume, recovered green veneer and roundup loss. The lower log is shown in grey and the upper log in white. The species (*Eucalyptus nitens*, Nit; or *E. globulus*, Glob), silvicultural regime (thinned and pruned, Th & Pr), average annual rainfall and age at felling (years) are shown for each site (Strathblane, St; Geeveston, Ge; Florentine, Fl; Deans Marsh, De; Orford, Or and Mumbannar, Mu) at the bottom of the panel. Y-axis labels are given in the graph titles. Sites with common letters were not significantly different at  $P < 0.05$  following a Tukey-Kramer adjustment for multiple comparisons

harvested at a similar age and yielded logs of similar diameter, is more difficult to explain. Further investigation of the possible drivers of this difference—genetic, environmental or silvicultural—is warranted.

#### 4.2 Recovery traits

The mean peelable billet volume (77 % of log volume) and green veneer recovery (78 %) were greater than those obtained in past studies of these and other plantation eucalypts

(Blakemore et al. 2010; Thomas et al. 2009; Luo et al. 2013; McGavin et al. 2014), explained in part at least by the use of a splindless lathe, the relatively large log diameters and the use of different measures of green veneer recovery across studies (McGavin et al. 2014; Luo et al. 2013). However, the lack of a statistical difference among sites for recovered green veneer is difficult to explain given that there was a highly significant difference among sites for peelable billet volume (Table 2). Conceptually, these traits should be equivalent, excluding small amounts of waste veneer disposed of at the initiation and/or cessation of peeling.

Although no statistically significant site by log position interaction effect was evident for any log recovery trait, there was generally a greater difference between the upper and lower log at the *E. nitens* sites than at the *E. globulus* sites, likely reflecting the same trend observed in out-of-roundness. In general, peelable billet volume and recovered green veneer was greater in the upper log than the lower log. However, the ranking of the upper and lower log was aberrant at the Deans Marsh site, also reflecting the trend observed in out-of-roundness and the presence of large bumps over occluded pruned knots. Anecdotally, bumps were more prevalent in the upper log than the lower log and resulted in the need for the removal of a greater proportion of wood during roundup. Deans Marsh also had the overall lowest peelable billet volume (Fig. 2a) and greatest roundup loss (Fig. 2c) as well as a large proportion of over-sized residual cores, attributable to the large amount of decay observed in logs from this site.

The greater recovery in the smaller-diameter upper logs (Fig. 2) and the fact that SEDUB did not explain significant levels of variation in recovery traits (Table 3) contradict some past studies (Thomas et al. 2009; Blakemore et al. 2010). However, in our study, there was a relatively small difference in diameter between the upper and lower log and relatively large differences in other log characteristics, most notably out-of-roundness, sweep and taper (Fig. 1). Luo et al. (2013) also noted that decreases in diameter with height did not result in decreased green recoveries and attributed this to the overriding impact of greater sweep and taper in lower logs.

Based on our study, the measurement of the log traits SEDUB, sweep, taper, out-of-roundness, end splitting and  $MOE_{dyn}$  does not represent a precise or practical means of estimating green veneer recovery at the log level for research or operational purposes. However, the amount of variation in recovery traits explained by measurements made on logs was substantially lower than in a study of diverse hybrid and pure species clones by Luo et al. (2013), in which nearly 80 % of variation in recovery in the lower log was explained by a combination of sweep, taper and circularity. Possible explanations for this difference across studies include the larger SEDUB of logs in the current study, species differences across studies and the fact that measurements by Luo et al. (2013) were made directly on 1.3-m billets, rather

than on 2-m logs prior to docking. It is also noteworthy that the production system in the current study was unique to this research-scale study. Under an operational production system, a stronger relationship between log traits and green recovery might be observed. Furthermore, at the site level, the site with the greatest out-of-roundness, Deans Marsh, exhibited the lowest peelable billet volume, hinting that it might be possible to develop tools to classify plantation coupes/estates according to green veneer recovery predicted from measurements made on a small sample of standing trees. Accordingly, an improved understanding of the standing-tree traits that affect green veneer recovery and means of manipulating these traits through genetics, site selection, management or log segregation could increase resource value and efficiency of use.

The significant difference in SEDOB between billets with over-sized and target-sized residual cores could have been due to a relationship between tree diameter (a function of growth rate and harvest age) and other traits affecting residual core diameter, such as wood properties, branching characteristics and decay. However, it is also possible that the difference was driven by the characteristics of one or more individual sites. For example, the Geeveston site had the largest diameter logs and the highest proportion of over-sized residual cores and this high proportion of over-sized cores might have been due to an unknown but inherent characteristic of this site. Although the Geeveston site also had the greatest log end splitting, which might be expected to adversely affect residual core diameter, there was no significant difference in log end splitting between logs with over-sized residual cores and logs with target-sized residual cores.

## 5 Conclusion

Temperate plantation eucalypts can yield high levels of green veneer recovery. Differences in percentage peelable billet volume, percentage roundup loss and residual core were evident among plantation sites, despite their being no discernable differences among sites in percentage recovered green veneer volume. The smaller-diameter upper log exhibited greater green recovery than the lower (butt) log, possibly due to greater sweep, taper and out-of-roundness in the lower log. Differences among sites for traits measured on logs were evident and, in the case of dynamic modulus of elasticity, alluded to differences in wood quality among sites. At the individual log level, a significant proportion of variation in recovery traits was explained by traits measured on logs, most notably out-of-roundness. Green veneer recovery is only the first step in the commercial production of veneer and veneer-based engineered wood products, and further research into veneer grade recovery and utility after drying is required to further guide decisions on species selection, site selection, forest management and product use.



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## References

- Arnold RJ, Xie YJ, Midgley SJ, Luo JZ, Chen XF (2013) Emergence and rise of eucalypt veneer production in China. *Int For Rev* 15:33–47
- Beadle C, Medhurst J, Forrester D (2011) Linking silvicultural management to solid-wood values. In: Walker J (ed) *Developing a eucalypt resource: learning from Australia and elsewhere*. Wood Technology Research Centre, University of Canterbury, Christchurch, pp 77–92
- Blackburn D, Farrell R, Hamilton M, Volker P, Harwood C, Williams D, Potts B (2012) Genetic improvement for pulpwood and peeled veneer in *Eucalyptus nitens*. *Can J For Res* 42:1724–1732
- Blackburn DP, Hamilton MG, Harwood CE, Baker TG, Potts BM (2013) Assessing genetic variation to improve stem straightness in *Eucalyptus globulus*. *Ann For* 70:461–470
- Blakemore P, Morrow A, Washusen R, Harwood C, Wood M, Ngo D (2010) Evaluation of thin-section quarter-sawn boards and rotary veneer from plantation-grown *Eucalyptus nitens*. vol Technical Report 202. Cooperative Research Centre for Forestry, Hobart
- Brancheriau L, Bailleres H (2002) Natural vibration analysis of clear wooden beams: a theoretical review. *Wood Sci Technol* 36:347–365. doi:10.1007/s00226-002-0143-7
- Downes G, Worledge D, Schimleck L, Harwood C, French J, Beadle C (2006) The effect of growth rate and irrigation on the basic density and kraft pulp yield of *Eucalyptus globulus* and *E. nitens*. *N Z J For Sci* 57:13–22
- Farrell R, Blum S, Williams D, Blackburn D (2011) The potential to recover higher value veneer products from fibre managed plantation eucalypts and roaden market opportunities for this resource: part A. *Forest & Wood Products Australia*, Melbourne
- Kibblewhite RP, Johnson BI, Shelbourne CJA (2000) Kraft pulp qualities of *Eucalyptus nitens*, *E. globulus*, and *E. maidenii*, at ages 8 and 11 years. *N Z J For Sci* 30:447–457
- Kubler H (1988) Silvicultural control of mechanical stresses in trees. *Can J For Res* 18:1215–1225
- Luo JZ, Arnold R, Ren SQ, Jiang Y, Lu WH, Peng Y, Xie YJ (2013) Veneer grades, recoveries, and values from 5-year-old eucalypt clones. *Ann For Sci* 70:417–428. doi:10.1007/s13595-013-0268-x
- McGavin RL, Bailleres H, Lane F, Blackburn D, Vega M, Ozarska B (2014) Veneer recovery analysis of plantation eucalypt species using spindleless lathe technology. *Bioresources* 9:613–627
- McKinley RB, Shelbourne CJA, Low CB, Penellum B, Kimberley MO (2002) Wood properties of young *Eucalyptus nitens*, *E. globulus*, and *E. maidenii* in Northland, New Zealand. *N Z J For Sci* 32:334–356
- Medhurst J, Downes G, Ottenschlaeger M, Harwood C, Evans R, Beadle C (2012) Intra-specific competition and the radial development of wood density, microfibril angle and modulus of elasticity in plantation-grown *Eucalyptus nitens*. *Trees Struct Funct* 26:1771–1780. doi:10.1007/s00468-012-0746-z
- Mohammed C, Battaglia M, Wardlaw T, Smith A, Pinkard E, Glen M, Tommerup I, Potts B, Vaillancourt R (2003) *Mycosphaerella* leaf diseases of temperate eucalypts around the southern pacific rim. *N Z J For Sci* 33:362–372
- Okuyama T, Doldan J, Yamamoto H, Ona T (2004) Heart splitting at crosscutting of eucalypt logs. *J Wood Sci* 50:1–6. doi:10.1007/s10086-003-0533-y
- Pinkard EA, Mohammed C, Beadle CL, Hall MR, Worledge D, Mollon A (2004) Growth responses, physiology and decay associated with pruning plantation-grown *Eucalyptus globulus* Labill. and *E. nitens* (Deane and Maiden) Maiden. *For Ecol Manag* 200:263–277
- Potts B, Hamilton M, Blackburn D (2011) Genetics of eucalypts: traps and opportunities. In: Walker J (ed) *Developing a eucalypt resource: learning from Australia and elsewhere*. Wood Technology Research Centre, University of Canterbury, Christchurch, pp 1–26
- Shi S, Walker J (2006) Wood-based composites: plywood and veneer-based products. In: Walker JCF (ed) *Primary wood processing: principles and practice*, 2nd edn. Springer, Dordrecht, pp 391–426
- Thomas D, Joe B, Austin S, Henson M (2009) Characterisation of plywood properties manufactured from plantation grown eucalypts. *Forest & Wood Products Australia*, Melbourne
- Wardlaw T (2011) A climate analysis of the current and potential future *Eucalyptus nitens* and *E. globulus* plantation estate on Tasmanian State forest. *Tasforests* 19:17–27
- Warensjo M, Rune W (2004) Stem straightness and compression wood in a 22-year-old stand of container-grown Scots pine trees. *Silva Fenn* 38:143–153
- Washusen R (2011) Processing plantation grown *Eucalyptus globulus* and *Eucalyptus nitens* for solid wood products—is it viable? Cooperative Research Centre for Forestry, Hobart
- Washusen R, Harwood C, Morrow A, Northway R, Valencia JC, Volker P, Wood M, Farrell R (2009) Pruned plantation-grown *Eucalyptus nitens*: effect of thinning and conventional processing practices on sawn board quality and recovery. *N Z J For Sci* 39:39–55
- Wolfinger R, Chang M (1995) Comparing the SAS GLM and MIXED procedures for repeated measures. In: *Proceedings of the Twentieth Annual SAS Users Group Conference*, Cary, NC. SAS Institute Inc
- Wood MJ, McLarin ML, Volker PW, Syme M (2009) Management of eucalypt plantations for profitable sawlog production in Tasmania, Australia. *Tasforests* 18:117–130
- Yang JL (2005) The impact of log-end splits and spring on sawn recovery of 32-year-old plantation *Eucalyptus globulus* Labill. *Holz Roh Werkst* 63:442–448. doi:10.1007/s00107-005-0035-2