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Patterns of longitudinal within-tree variation in pulpwood and solidwood traits differ among *Eucalyptus globulus* genotypes

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Abstract – Wood discs were sampled from 6 heights up the stem of 248 trees representing 10 subraces and 116 families grown in an *E. globulus* base-population progeny trial. The lower stem had the least favourable wood properties for kraft pulpwood and most solidwood applications: bark was thickest, basic density was lowest and kino, decay and shrinkage traits were greatest at or below 12% of tree height. Significant genetic differences at the subrace level were revealed in diameter, bark thickness, basic density, decay and gross shrinkage and at the family within subrace level in diameter, basic density and decay. However, subrace-by-height-category interactions in bark thickness, basic density, decay and gross shrinkage indicated that differences among subraces were dependent on height in these traits. Examination of longitudinal trends revealed some evidence that the zone of thick basal bark extended further up the stem in thicker-barked subraces and that the Southern Tasmania subrace might be less effective than other subraces in restricting the longitudinal spread of decay after infection.

wood properties / *Eucalyptus globulus* / longitudinal variation / within-tree variation / genetic variation

Résumé – Les variations longitudinales intra-arbre des propriétés papetières et du bois varient entre les génotypes d'*Eucalyptus globulus*. Des disques de bois ont été prélevés à 6 hauteurs différentes dans 248 arbres représentant 10 provenances et 116 familles d'un dispositif de provenance-descendance d'*E. globulus*. La partie inférieure des troncs présente les propriétés du bois les moins bonnes pour la pâte Kraft et la plupart des utilisations du bois massif : l'écorce est plus épaisse, l'infradensité plus faible tandis que le kino, la dégradation biologique et les retraits sont plus importants jusqu'à 12 % de la hauteur des tiges. Des différences génétiques significatives ont été établies au niveau provenance pour le diamètre, l'épaisseur d'écorce, l'infradensité et la dégradation biologique et au niveau famille dans une provenance pour l'infradensité et la dégradation biologique. Cependant, pour ces propriétés, les interactions provenance par catégorie de hauteur, pour l'épaisseur d'écorce, l'infradensité, la dégradation biologique et le retrait total, indiquent que les différences entre provenances dépendent de la hauteur. L'analyse des variations longitudinales fait apparaître que la longueur de la bille de pied ayant une écorce plus épaisse est plus importante pour les provenances présentant des écorces épaisses et que les provenances de sud de la Tasmanie pourraient être moins efficaces que les autres pour limiter la diffusion des pourritures après infection.

propriétés du bois / variation longitudinale / variation intra arbre / variation génétique / *Eucalyptus globulus*

1. INTRODUCTION

Eucalyptus globulus Labill. (Tasmanian Blue Gum; sensu Brooker [9]) is native to south-eastern Australia and is one of the most important pulpwood plantation species in temperate regions of the world. Substantial areas of plantation are grown for this purpose in Australia, Chile, Portugal and Spain [27]. However, there is growing interest in using plantation-grown *E. globulus* to produce sawn timber and reconstituted solidwood products [23].

For breeding and mensurational purposes it is desirable to estimate whole-tree wood quality values for commercially important traits using cheap and non-destructive sampling techniques. Knowledge of within-tree variation is required to determine the most representative point to sample or measure and to develop relationships between point estimates and whole-tree values [30]. Mensurationists also use knowledge of

longitudinal within-tree variation to estimate yields of individual product classes (e.g. log sizes by diameter and length [21]). Similarly, timber processors can use such knowledge to ensure trees are used in the most appropriate and profitable manner by modifying processing practices or allocating logs to particular end uses according to the known properties of different stem sections.

Longitudinal variation in diameter, bark thickness, basic density and shrinkage traits has previously been studied in *E. globulus* [16, 19, 28, 30, 31, 41]. However, with the exception of Guimaraes et al. [16], these studies did not investigate if patterns of longitudinal variation differed among intra-specific genotypes. If present, such differences in longitudinal variation (i.e. genotype-by-height interaction) may introduce bias according to genotype in estimates of whole-tree values and/or the characteristics of specific stem sections derived from sample measurements.

This study examines longitudinal variation in diameter under bark, bark thickness, basic density, kino, decay and

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Table I. Summary of felled trees by subrace.

Subrace	Number of families	Number of trees	Mean DBHOB [§] (cm)	Mean height (m)
Cape Patton*	9	18	29.2	24.5
Eastern Otways*	10	21	28.0	24.1
Flinders Island**	13	27	30.0	25.3
King Island	13	28	31.5	25.5
Southern Furneaux**	9	18	28.7	23.5
Southern Tasmania	10	21	27.6	25.1
South-Eastern Tasmania	11	24	27.8	23.7
Strzelecki Ranges (incl. Madalya Rd.)	18	37	28.9	24.6
Western Otways	13	32	30.0	25.8
Western Tasmania	10	22	26.2	24.3
Total	116	248	28.9	24.7

* Eastern Otways race, ** Furneaux race, [§] diameter at breast height (1.3 m) over bark.

shrinkage properties of *E. globulus*. Furthermore, it investigates whether patterns of longitudinal variation are consistent across subraces and families within subraces. Differences among genotypes are discussed in this context.

2. MATERIALS AND METHODS

This study was undertaken on trees planted in a *E. globulus* base-population progeny trial (Gunns Ltd.) growing at West Ridgley in north-western Tasmania (for details see Apiolaza et al. [1] and MacDonald et al. [18]). The trial was divided into two areas approximately 150 m apart containing two and three replicates respectively.

This study was undertaken on 248 trees from 116 families and 10 subraces (refer to Dutkowski and Potts [11], updated according to the findings of Lopez et al. [17] at <http://members.forestry.crc.org.au/globulus/>) felled as part of a sawmilling trial [15]. Of these, 58 trees from 32 families and 6 subraces had previously been cored or assessed for pilodyn penetration at or near breast height (1.3 m) [1, 11, 18]. The ten subraces, from eight races, were selected because of their commercial importance and wide distribution across the natural geographic range of *E. globulus* (Tab. I). Between 9 and 18 families per subrace were selected for study from up to six seed collection localities within each subrace so as to encompass a wide range of genetic diversity. To enable extraction of a sawlog from each tree, trees within families were selected on the basis of diameter and stem straightness. Average felled-tree heights and diameters at breast height over bark are presented by subrace in Table I. A single 1.5 m long sawlog was cut from the straightest part of the lower stem in each tree [15]. At the time of sampling, 15 years after establishment, the trial had not been thinned or pruned (i.e. it had been managed as a pulpwood stand) but 54% of the original trees had died.

Wood discs, approximately 25 mm thick, were extracted from six heights within each tree. The mean height of discs within each of the height categories was 0%, 5% (breast height, BH), 12% (base-of-sawlog, BSL), 18% (top-of-sawlog, TSL), 40% and 60% of tree height. The percentage height of individual breast height, base-of-sawlog and top-of-sawlog discs varied between trees due to differences in tree height and/or the height at which sawlogs were extracted. After extraction, the discs were immediately placed in plastic bags to minimise moisture loss.

Disc diameter under bark (DUB) was measured using a diameter tape. Bark thickness was measured using callipers, multiplied by two and expressed as a percentage of diameter over bark. Photographs of green discs were used to visually assess the extent of

kino [12] and decay. To assess kino, discs were visually divided into eight radially-oriented sectors of equal size and the number of sectors with kino veins and/or pockets tallied. White or light-coloured decay was generally observed to radiate from the pith. Decay in each disc was scored as a percentage of the disc radius affected: 0%, 1–20%, 21–40%, 41–60%, 61–80% and 81–100%. Less advanced and less visibly obvious (i.e. incipient) decay was present but not considered in the visual assessment.

Whole discs were deemed impractically large for processing and transport and were sawn through the pith into symmetrical half-discs (i.e. where stem eccentricity was evident, areas deemed most likely to contain a high proportion of tension wood fibres were distributed evenly between half-discs). One half-disc was randomly selected for assessment and the other discarded. Debarked green volumes of the selected half-discs were measured using the water displacement method [35]. The half-discs were then pre-dried [22] in a kiln to a moisture content of approximately 20%.

During pre-drying, the half-discs shrank and bent at their pith [15] due to higher tangential than radial gross shrinkage (i.e. shrinkage anisotropy), the primary explanation for cupping and some forms of cracking (i.e. checking) in back-sawn boards [34]. Gross shrinkage angle was measured as the angle formed between one half of the cut (i.e. radial) surface of each half-disc and a flat surface, against which the other half of the cut surface was held. The half-discs were then steamed (i.e. reconditioned) to recover collapse [10,22]. Finally, discs were air-dried in a sheltered area to equilibrium moisture content (approximately 13%). After air-drying, net shrinkage angle was measured using the same procedure used to measure gross shrinkage angle. Discs that split during drying were excluded from analyses. Finally, the half-discs were oven dried at 105 °C, weighed and their basic densities calculated [35].

Separate restricted maximum likelihood (REML) mixed model analyses were conducted for each trait. The model fitted area, height category, subrace and subrace-by-height-category interaction as fixed effects, height category by percentage disc height as a covariate and replicate within area, family within subrace (hereafter referred to as 'family') and family-by-height-category interaction as random effects. An unstructured within-tree residual variance/covariance matrix, allowing for different residual variances at each height category, was fitted to account for within-tree covariation among height categories. The height category by percentage disc height covariate was fitted for the breast height, base-of-sawlog and top-of-sawlog height categories only, as percentage disc height was invariable in the other height categories. Fourteen outlying observations from three

Table II. Significance tests for genetic, stem height and interaction effects from analysis of growth and wood quality traits. F-test ratios are reported for fixed effects.

Trait	Fixed effects			Random effects	
	Subrace	Height category	Subrace-by-height-category	Family within subrace	Family-within-subrace-by-height-category
Logarithm of diameter under bark	3.0 **	2126 ***	1.0 ^{ns}	**	ns
Bark thickness	32.8 ***	272 ***	3.2 ***	ns	ns
Basic density	4.1 ***	99 ***	1.4 *	**	ns
Kino	1.0 ^{ns}	37 ***	1.0 ^{ns}	ns	ns
Gross shrinkage angle	1.1 ^{ns}	136 ***	1.9 ***	ns	ns
Net shrinkage angle	1.7 ^{ns}	23 ***	1.2 ^{ns}	ns	ns

^{ns} Not significant, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

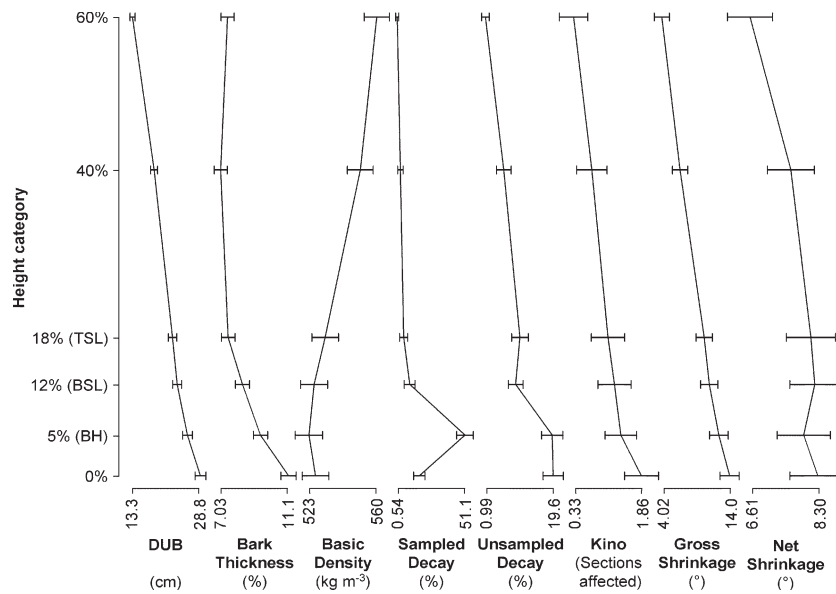


Figure 1. Height category means and 95% confidence intervals for all traits under consideration. DUB is the back-transformed diameter under bark and thus 95% confidence intervals are asymmetric. Maximum and minimum height category least squares means are presented for each trait on the x axis.

traits were excluded from final analyses as they unambiguously represented measurement or data-entry errors. Analyses were undertaken using ASReml. The significance of the fixed effects were gauged with F-tests and random effects were tested using likelihood ratio tests [13, 32].

Diameter under bark data were logarithm transformed prior to analysis. Decay was initially fitted as a fixed effect in the analysis of basic density. It was found to significantly affect basic density but its exclusion from the model did not change the interpretation of the subrace, family or interaction effects, the principal foci of this study.

Decay was analysed separately for each height category due to heterogeneous error variances even after arcsine square root transformation. Furthermore, observation at the time of disc extraction suggested that decay was greater in trees that had previously been sampled for wood cores or assessed for pilodyn penetration. Analyses revealed a significant subrace by sampling category (i.e. previously sampled or unsampled) interaction in some height categories, indicating that differences in decay among subraces were different in the previously sampled and unsampled groups of trees. Accordingly, separate analyses were undertaken on data from each height category within sampling category.

Trait least square means and 95% confidence intervals were estimated at the mean percentage disc height within each height category. For those traits in which a significant subrace-by-height-category interaction was identified, separate analyses were undertaken for each height category. Subrace least squares means were estimated at the mean percentage disc height within each height category to enable interpretation of subrace-by-height-category interactions.

3. RESULTS

Height category had a highly significant effect on diameter under bark, bark thickness, basic density, kino, and gross and net shrinkage angle (Tab. II). In general, bark thickness rapidly decreased with height in the lower stem before stabilising towards and slightly increasing above 40% of tree height. Overall, basic density also tended to decrease with height from the base before increasing between 5% and 60% of tree height and kino, gross shrinkage and net shrinkage generally decreased with height (Fig. 1). However, specific patterns of longitudinal variation were found to vary among

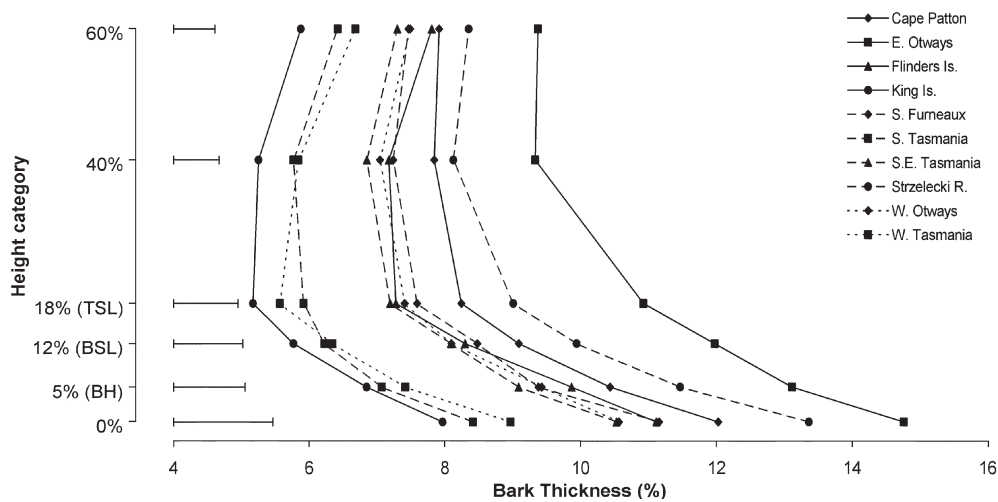


Figure 2. Subrace least squares means for bark thickness within height categories. The lengths of the bars are equal to 1.96 times the overall standard error of difference between subraces within each height category.

subraces in bark thickness, basic density and gross shrinkage angle, as indicated by the significant subrace-by-height-category interactions in these traits (Tab. II). Overall significant differences between subraces were identified in diameter under bark, bark thickness and basic density. Significant family variation was observed in diameter under bark and basic density but no significant family-by-height-category interaction effects were identified in any of the traits analysed using the full model.

Although the magnitude of differences in bark thickness between subraces varied, the rankings of subraces were similar across height categories (Fig. 2) and highly significant differences between subraces ($P < 0.001$) were identified at all heights when analysed separately. Furthermore, there was some evidence that the zone of thick basal bark extended further up the stem in thick-barked (e.g. Eastern Otways and Strzelecki Ranges) than in thin-barked subraces (e.g. King Island and Western Tasmania; Fig. 2).

Separate height category analyses of basic density revealed significant differences ($P \leq 0.045$) between subraces at all heights except the base-of-sawlog. The King Island and South-Eastern Tasmania subraces had below average and the Eastern Otways and Strzelecki Ranges had above average basic density in all height categories.

Substantially more variation in gross shrinkage angle among subraces was observed in the lower three height categories than those further up the stem. Analysis within individual height categories revealed significant differences between subraces at 0% of tree height ($P = 0.011$) and breast height ($P = 0.009$). South-Eastern Tasmania exhibited relatively low levels of gross shrinkage and was ranked in the top three subraces in all height categories. Conversely, Flinders Island exhibited high gross shrinkage and was ranked in the bottom two subraces in all height categories except 60%.

Although significant differences in shrinkage traits were observed between height categories and/or genotypes, it is possible that the magnitude of these differences were under-

estimated in this study. There was some evidence for positive correlations of disc splitting with diameter and shrinkage angle and, as split discs were excluded from analyses, mean shrinkage angle in height categories and genotypes with a higher underlying shrinkage angle and/or larger diameter may have been underestimated. Twenty-two percent of the half-discs split during pre-drying and a further 34% split during reconditioning and final-drying.

The most notable feature of longitudinal variation in decay in previously sampled trees was a large peak at breast height (Fig. 1). However, if breast height was excluded, decay levels were similar at each height category (e.g. 16.9% and 19.6% at 0% of tree height in previously sampled and unsampled trees respectively) and there was a general trend toward diminishing decay with height in both the previously sampled and unsampled groups of trees. Very little decay was observed in the 40% and 60% height categories.

In the previously sampled group, significant differences in decay between subraces were observed in the 0% ($P = 0.024$) and base-of-sawlog height categories ($P = 0.015$). Notably high decay was observed in the Southern Tasmania subrace at the base- and top-of-sawlog (Fig. 3). In the previously unsampled group, the subrace term was significant at the top-of-sawlog only ($P = 0.009$). At heights in which significant differences between subraces were identified, the Southern Tasmania subrace contained the most decay in both previously sampled (Fig. 3) and unsampled (Tab. III) trees. In contrast, the Strzelecki and Flinders Island subraces exhibited little decay in both sampled and unsampled trees.

In previously unsampled trees, significant family variation in decay was found in the 0% ($P = 0.009$) and breast height ($P = 0.031$) categories. In sampled trees, no significant family variation was observed. The presence of significant differences among subraces and families in the lower stem and extremely low decay levels in the upper stem was indicative of genotype-by-height-category interaction.

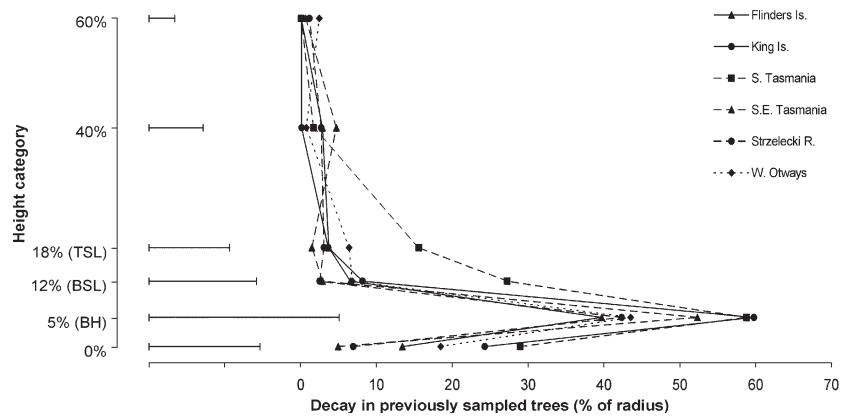


Figure 3. Subtrace least squares means for decay in previously sampled trees within height categories. Only subtraces previously sampled for wood property assessment are shown. The lengths of the bars are equal to 1.96 times the overall standard error of difference between subtraces within each height category.

Table III. Subtrace least squares mean decay levels from previously unsampled trees within the top-of-sawlog height category. Mean decay is expressed as a percentage of disc radius.

Subtrace	Mean decay (%) (SE)
Flinders Island	7.0 (4.8)
Strzelecki Ranges (including Madalya Rd.)	8.2 (4.2)
King Island	8.5 (4.8)
Western Tasmania	9.1 (4.6)
South-Eastern Tasmania	11.0 (4.6)
Eastern Otways	11.8 (4.5)
Southern Furneaux	14.5 (4.8)
Cape Patton	15.4 (4.7)
Western Otways	21.2 (4.7)
Southern Tasmania	25.9 (5.2)

4. DISCUSSION

4.1. Longitudinal variation

The longitudinal trends observed in bark thickness and basic density (Fig. 1) were consistent with previous findings for *E. globulus* [19, 28, 30]. The distinct peak in decay at breast height observed in the sampled group of trees was almost certainly caused by fungi that infected stems through wounds associated with previous sampling for wood property assessment (Fig. 1). Sampling-induced decay has the potential to modify both the physical and chemical properties of wood in standing trees. Therefore, individual trees should be sampled for these traits only once. The observed longitudinal variation in kino score may have been due to longitudinal variation in physiology, longitudinal variation in the risk of injury to the cambium [12] and/or the fact that the base of trees were exposed to such injury from a young age. The longitudinal trend in gross shrinkage angle was consistent with trends observed in other studies of shrinkage traits and tension wood [31, 41].

The lower basic density, greater decay, greater kino, and higher gross and net shrinkage angle observed in the lower stem are likely to have negative implications for the processors of plantation-grown *E. globulus* wood. High basic density

is desired for kraft pulp [8, 14] and most solidwood products [5, 29, 42], the presence of decay or kino can result in degrade in solidwood products [2–4] and timber exhibiting high shrinkage angle is likely to be more prone to drying degrade. Suboptimal expression of these traits in the lower stem disproportionately affects whole-tree economic value because the lower stem represents a high proportion of total stem volume and produces logs of the largest diameter. Large diameter logs yield wide boards and high green recoveries in sawmills [37] and exhibit high conversion volumes per unit time in veneer mills [33].

Although suboptimal, the longitudinal trends observed in this study may not preclude the use of plantation-grown *E. globulus* wood in the manufacture of any given product. For example, plantation-grown *E. globulus* is sought after for kraft pulp production [27]. Furthermore, decay and kino have been shown to be of secondary importance compared to other sources of degrade, such as knots and drying defects, in sawmilling trials [40, 42, 43]. There is also evidence that plantation-grown *E. globulus* can be dried to meet appearance specifications if suitable sawing (e.g. quarter-sawing) and drying (e.g. controlled kiln drying) strategies are adopted [38, 39], albeit at potentially greater production cost and with lower recovery of green timber [7, 23]. Additionally, it is possible that observed longitudinal trends in some traits are not representative of what would occur under solidwood silviculture. For example, the extent of decay in some height categories might have been different if the trial had been thinned and pruned [25, 36, 37].

4.2. Genotype-by-height-category interaction

The significant subtrace-by-height-category interaction detected in bark thickness (Tab. II) appeared to be caused by changes in the magnitude of differences between subtraces with height without extensive changes in their ranking. Dutkowski and Potts [11] suggested that thicker bark could be an adaptation to higher fire frequency and water stress. The extension

of the zone of thick basal bark further up the stem observed in thick-barked subraces may be a further adaptation to these environmental factors.

Estimates of subrace least squares means for gross shrinkage angle and basic density within height categories were not precise enough to enable meaningful discussion of variation in longitudinal trends among subraces. However, high decay at the base-of-sawlog indicated that the Southern Tasmania subrace might be less effective in restricting the longitudinal spread of decay than other subraces (Fig. 3). The presence of extremely low levels of decay in the upper stem and significant differences among families in the lower stem indicated that longitudinal trends in decay were different among families in previously unsampled trees. Accordingly, measurement of decay for breeding purposes should be undertaken at a consistent height in the lower stem.

4.3. Differences between genotypes

The rankings of subraces for bark thickness (Fig. 2) were consistent with those observed by Dutkowski and Potts [11] and Lopez et al. [17]. The generally low basic densities of King Island and South-Eastern Tasmania and high basic densities of the Eastern Otways and Strzelecki Ranges were also consistent with the findings of other studies [11, 17, 20]. Furthermore, Poke et al. [26] reported that localities they studied from within the Strzelecki and Flinders Island subraces exhibited relatively low levels of decay, as was the case in this study.

The absence of significant genotype-by-height-category interactions in the logarithm of diameter under bark indicated that the ratios of untransformed diameters between height categories, and thus the shape of stems [6], were not significantly different among genotypes. However, given the limited number of trees felled in this study, minor differences in stem shape may not have been detected. Although not directly comparable with the findings of the current study, Guimaraes et al. [16] identified significant differences in tree taper parameters among *E. globulus* provenances.

The significant differences in bark thickness observed among subraces suggested that estimates of under-bark diameter, and thus under-bark whole-tree volume and log sizes [21, 24], derived from over bark measurements would be improved with the application of subrace specific relationships. Furthermore, tree volume equations and taper functions developed using data from plantations established prior to the mid 1990's may not be accurate when applied to plantations established since, because the mix of subraces grown has changed considerably over the past 15 years [27].

The lack of significant differences in kino among genotypes indicated that breeding is unlikely to be a useful means of reducing kino in plantation grown *E. globulus*. However, the assessment of kino induced in a controlled manner across genotypes through deliberate injury of the cambium [12] may have been more likely to reveal significant genetic differences.

5. CONCLUSION

The lower stem had the least favourable wood properties for kraft pulpwood and most solidwood applications: bark was thickest, basic density was lowest and kino, decay and shrinkage angle were greatest at or below 12% of tree height. These longitudinal trends have adverse implications for forest managers and wood processors given that the lower stem represents a high proportion of total stem volume and produces logs of the greatest diameter.

Although there was indirect evidence of such an interaction in decay, significant family-within-subrace-by-height-category interaction was either not present in other traits or not detectable given the limited number of trees felled for this study. Evidence of subrace-by-height-category interaction was identified in bark thickness, basic density, decay and gross shrinkage angle indicating that patterns of longitudinal variation in these traits differed among subraces. However, the ability to interpret these interactions and discuss their implications varied among traits.

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