BREEDING TO MINIMISE THE EFFECTS OF COLLAPSE IN *EUCALYPTUS NITENS* SAWN TIMBER

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ABSTRACT

Checking and collapse have been identified as major causes of degrade for appearance grade boards produced from *Eucalyptus nitens* pruned logs. The normal methods for managing these problems are through selection of sawing and drying techniques. This paper evaluates tree breeding as a means of managing this problem.

Genetic parameters were estimated for tangential collapse measured on 12 mm wood cores taken at 0.9 m height. Data were collected from 12 year old *E. nitens* progeny trials in Tasmania. Collapse was under moderate to strong genetic control. Heritabilities across sites varied from 0.23 to 0.61 and for a combined site analysis the heritability was 0.38. The genetic correlation between collapse and basic density was strongly favourable (r_g = –0.75) but correlations between collapse and diameter, and collapse and cellulose content were strongly adverse (r_g = 0.75 and 0.54 respectively). There was no genotype by environment interaction for collapse.

A hypothetical model for predicting checking from collapse was used to predict product out turn of appearance board grades and some different selection strategies are discussed. Selecting for diameter alone is predicted to cause a large increase in checking, resulting in very few boards being acceptable for the joinery market. Selecting on a diameter and basic density index is expected to cause no change in checking and therefore this is a reasonable option if current wood quality is acceptable for the appearance grade market. Selecting on an index of diameter and collapse measured on increment cores is predicted to lower the incidence of checking to a point where most boards will be suitable for the joinery market.

Key words: *Eucalyptus nitens*, genetic gains, genetic parameters, sawn timber, collapse, wood checking

INTRODUCTION

Eucalyptus nitens (Deane & Maiden) Maiden is a common hardwood plantation species in cool-temperate regions. The global plantation area was approximately 220,000 ha in 1999 and the main plantation areas were in Australia (Tasmania and Victoria), Chile, South Africa and New Zealand (TIBBITS et al. 1997). *E. nitens* is mostly grown for pulpwood, however, in Tasmania, where the majority of Australian *E. nitens* plantations occur, this species is now being grown for veneer, appearance and structural products (NEILSEN & PINKARD 2000). *E. nitens* has many of the characteristics required for high quality appearance products. However, in saw milling trials the major causes of downgrade were knots and checking (MCKIMM *ET AL.* 1988; WAUGH & YANG 1994; MCKENZIE *et al.* 2003a). Knots are a problem in *E. nitens* because this species retains dead branches but this can be managed silviculturally by using pruning regimes (NEILSEN & PINKARD 2000).

Checking is a problem that occurs during drying and refers to the separation of the fibres along the grain to form a crack in the timber. These cracks can occur both internally and on the surface but do not extend through the piece of timber (HILLIS & BROWN 1978; JACOBS 1979). Collapse, which is a type of shrinkage in wood caused by the buckling of the cell walls and flattening of the lumens, is recognised as a major cause of checking (CAMPBELL & HARTLEY 1978; JACOBS 1979; CHAFE *et al.* 1992; ILIC 1999). Collapse is different from normal shrinkage in that it occurs as moisture is removed from the cell lumens (i.e. above fibre saturation point). Normal shrinkage occurs after water has been removed from the lumens, and is caused by the removal of water from the cell wall. Collapse is caused by hydrostatic tension forces within the cell and, when capillary size is small and cell walls thin, these forces exceed the compressive strength of the cell wall leading to a flattening of the cell (CHAFE 1985; CHAFE *et al.* 1992). Collapse in *E. regnans* has been found to be related to basic density, moisture content and shrinkage. However, these properties do not appear to explain any more than 20 % of variation in collapse (CHAFE 1985; ILIC 1999).

Collapse has been found to vary within trees. Problems appear to be most severe near the stump, and decrease along the length of the stem (PANKEVICIUS 1961; CHAFE 1985; PURNELL 1988; RAYMOND & SAVAGE, unpublished data). This may be a result of decreasing moisture content (via lower lumen saturation) and higher wood density (via thicker cell walls) along the length of the stem (CHAFE 1985). Regardless of the cause, this variation has serious implications for eucalypt sawlog plantations because the pruning regimes used for these plantations concentrate investment on the bottom log (NEILSEN & PINKARD 2000), which is the part of the tree where the problem will be at its worst.

Checking and collapse have been recognised as problems since utilisation of eucalypts began. Treatments to address these problems were first developed in 1917 and have been the subject of ongoing research (CHAFE *et al.* 1992). Essentially two methods for managing these problems have been developed. The first of these is the use of appropriate sawing techniques. Collapse manifests differently on radial (quarter sawn) and tangential (back sawn) faces of sawn wood (CAMPBELL & HARTLEY 1978; JACOBS 1979; CHAFE *et al.* 1992). On the quarter sawn face, collapse appears as a corrugated or 'washboard' surface with little or no surface checking. This problem can be easily overcome by cutting over size and then planing, although it does cause lower recovery. On the back sawn face collapse can cause internal and surface checking which is sometimes very severe. This can be partially managed by cutting thinner boards (25 mm) and by carefully air-seasoning prior to kiln-drying. The second method used to manage checking and collapse is 'reconditioning' which involves steaming boards for 2 to 6 hours at atmospheric pressure (JACOBS 1979; CHAFE *et al.* 1992). Steaming in this way softens cell walls without saturating the cell lumens and allows buckled cell walls to resume their normal shape. Reconditioning can close checks but the fractures remain and for some applications, such as moulding, this does not solve the problem.

Although sawing techniques and reconditioning have allowed the commercial utilisation of what were once uncommercial species (JACOBS 1979), they do not solve all problems and other management techniques are needed (CHAFE *et al.* 1992). This is likely to be also true for plantation grown *E. nitens* wood. Log sizes may be too small to quarter saw (WAUGH & YANG 1994) and therefore the saw miller will have fewer management options (JACOBS 1979). Furthermore, although saw milling studies on *E. nitens* have indicated checking will be within manageable limits (WAUGH & YANG 1994; MCKENZIE *et al.* 2003a), other studies suggest there will be severe checking problems on some sites which will limit its use as appearance grade timber (SHELBOURNE *et al.* 2002).

Tree breeding has often been suggested as a potential method for managing checking and collapse. Many studies report large variation between trees (e.g. PURNELL 1988; CHAFE *et al.* 1992) and genetic variation is usually suggested as the cause. Nevertheless, studies on the genetic variation in checking and collapse appear limited and tree breeding is not being used to manage collapse. Published studies on checking in eucalypts appear limited to a provenance study for *E. delegatensis* (KING *et al.* 1993), and a small study (5 seedlots) for *E. nitens* (PURNELL 1988). No studies appear to have been done on the genetic parameters of checking or collapse.

This study evaluates tree breeding as a tool to manage collapse and checking in *E. nitens*. It is part of a broader study that has reported on the genetic control of pulpwood traits and some sawlog traits (KUBE *et al.* 2001; KUBE 2004). There were three aims to this study. The first was to calculate the degree of genetic control and the amount of genotype by environment interaction for collapse. The second was to determine relationships between collapse and traits that are used in existing breeding programs (that is growth, basic density and pulp yield). And the third aim was to assess the potential of tree breeding to change the incidence of collapse (and therefore checking) and to explore options for using collapse in a breeding program.

MATERIAL AND METHODS

Trial establishment and assessment

The genetic material was open-pollinated progeny of 40 native forest families from the Toorongo Plateau in the central highlands of Victoria and the location is described in PEDERICK (1979). Mother trees were growing as a pure stand in an open forest and stem diameters ranged from 35 to 110 cm.

Progeny trials were established in 1984 on three sites in northern Tasmania, all with good soil fertility and good productivity (Table 1). Stocking at planting was 1111 trees ha^{-1} (3 m by 3 m spacing) and survival at age 12 years was 81%. The trial design was a randomised complete block with single tree plots and 16 replications per site. Fifteen of the 40 families were only planted at two sites. The 'missing' families were spread, in different combinations, across all sites and so every site had at least 35 families. Traits measured were diameter at breast height, basic density, cellulose content and collapse, and these are summarised in Table 2.

All trees were measured for diameter at breast height (1.3 m) at 12 years. Trees less than 10 cm diameter were excluded from diameter and wood property assessments. Trees of this size were all strongly suppressed with no diameter increment between ages 6 and 12, and had atypical wood properties. These trees were found to inflate error variances.

Basic density was measured at 12 years and was assessed using a single 12 mm diameter bark to bark core at a height of 0.9 m. Core sampling at this height has been shown to be a reliable predictor of whole tree values of basic density (RAYMOND & MUNERI 2001; KUBE & RAYMOND 2002). Basic density was defined as oven-dry wood mass per unit volume of green wood, and was measured using the water displacement method (TAPPI 1989). Samples were taken from all sites and between 5 and 13 trees per family per site were randomly sampled (average of 8). Following an initial analysis, 11 trees were excluded due to high residuals (greater than 3 standard deviations from mean density). These trees had low diameters, very little diameter increment between 6 and 12 years, and very high density.

Crude cellulose content (g cellulose per dry mass wood) was assessed at 13 years using 12 mm bark to bark core samples taken at a height of 0.9 m. Core sampling at this height has been shown to be a reliable predictor of whole tree values of cellulose content (KUBE & RAYMOND 2001). Wood cores were dried at 27 °C, ground and assayed using the method of Wallis *et al.* (1997). This method involves digesting in diglyme and hydrochloric acid to dissolve non-cellulosic compounds and then collecting the cellulose residue by filtration. Five trees were randomly sampled per family from each site. More details of the sampling and analysis are given in KUBE *et al.* (2001).

Tangential collapse was assessed on the same core as that used to measure basic density. Core sampling at this height has been shown to reliably predict average collapse in the bottom 6 m of the stem for *E. nitens* (RAYMOND & SAVAGE, unpublished data). After drying green cores at 105 °C, bands of very high shrinkage were observed on the cores (Figure 1). These shrinkage bands recovered fully after steam reconditioning for one hour and therefore it was assumed that the observed bands were due to collapse and not collapse-free or normal shrinkage or tension wood (CHAFE 1985; CHAFE *et al.* 1992). The degree of collapse was quantified by measuring

Table 1. Location and description of trial sites.

	Dial	Gog	Kamona
Latitude (South)	41°10′	41°29′	41°08′
Longitude (East)	146°04′	146°23′	147°40′
Altitude (m)	100	300	160
Rainfall (mm·$year^{-1}$)	1060	1200	1150
Mean max.temperature warmest month (°C)	22.3	21.8	23.4
Mean min. temperature coolest month (°C)	3.8	2.4	2.5

Table 2. Description of data used in analyses. SD is the standard deviation and n is the number of samples.

Trait		Age (years)	Min.	Mean	Max.	SD	*n*
D	Dbh age 12 (cm)	12	10.1	21.1	40.4	6.0	1160
BD	Basic density (kg m^{-3})	12	362	451	568	31	841
CEL	Cellulose content (% kg kg^{-1})	13	38.0	41.5	45.4	1.4	545
COL	Tangential collapse (%)	12	0	16.2	37.5	7.6	806

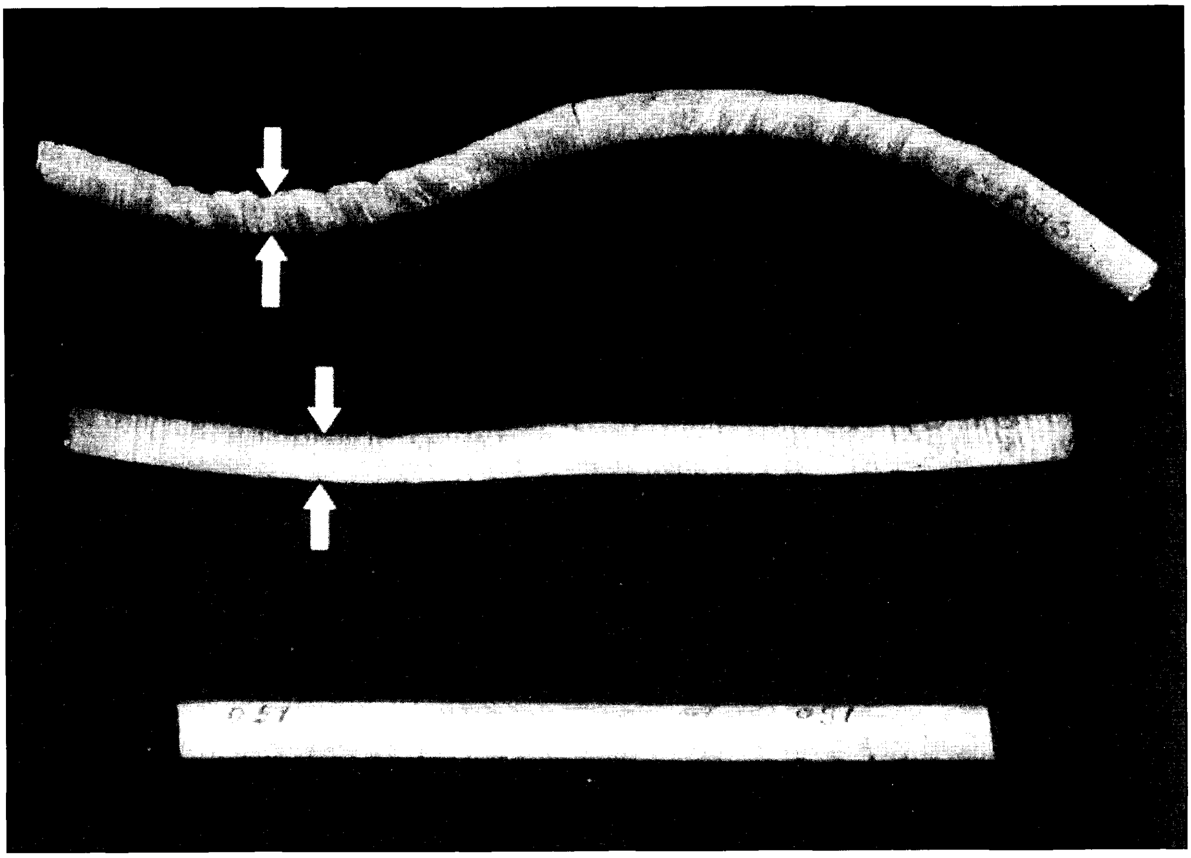

Figure 1. Location of shrinkage bands (see arrows) measured to assess collapse. The upper core is a sample with very high shrinkage bands and very high distortion after drying. The middle core is a sample with very low shrinkage bands and low distortion. The lower core is a sample following steam reconditioning where shrinkage bands and distortion have recovered.

tangential diameter at the narrowest point of each section of the bark to pith core. Since the cores used in this study were bark to bark cores, there were two measurements of 'collapse' per tree. This diameter was then expressed as the percentage loss relative to the tangential diameter at the pith after drying. The tangential diameter of the pith did not change before and after reconditioning. Sample trees were the same as those used for basic density measurements (an average of 8 trees per family per site).

Wood densities measured using x-rays techniques on SilviScan-2 (EVANS *et al.* 2000) were used for a small part of this study. Assessing wood density using x-rays allows very specific measurements to be made on individual growth rings and on variation within growth rings. Relationships between these measurements and collapse were explored. Wood samples were from an additional bark to bark core taken at a height of 0.9 m. This core was dehydrated in ethanol and dried at 25 °C. A thin bark to pith strip was cut from this core (2 mm tangentially and 7 mm longitudinally) and density was then measured at 0.05 mm intervals using Silviscan-2. For this study density measurements were only used from the growth rings formed at ages 6, 8 and 10 years. From these rings, three measurements were used and these were average density, minimum density and density differential, which was the difference between the maximum and minimum density within each measured ring. A total of 471 trees were sampled with 5 trees being sampled per family per site. Further details about the methods are given in EVANS *et al.* (2000).

Estimation of genetic parameters

All traits were analysed using ASREML (GILMOUR *et al.* 1999) and two models were fitted which are shown below. Multivariate analyses use information more efficiently and can improve the precision of genetic parameters when selected subsets of data are used (DIETERS *et al.* 1999). An example of their use is shown and discussed in APIOLAZA & GARRICK (2001). The first model (model 1) was a multivariate multisite model which was used to estimate variances, covariances, correlations and errors for each site and each trait simultaneously. The two models treat measurements on different sites as different traits and the first model was used for the analysis of sites separately. The second model (model 2) was a multivariate combined site model which estimated variances, genetic correlations and genotype by environment interactions when data were pooled across sites. Error variances for each trait were similar and therefore adjusting to a constant error variance was not considered necessary. The models were:

$$Y = \mu + SITE + REP + FAM(SITE) + \varepsilon \quad [1]$$

$$Y = \mu + SITE + REP + FAM + FAM.SITE + \varepsilon \quad [2]$$

where Y is a vector of data for each trait; μ is the mean for each trait; SITE are the site effects fitted as a fixed factor; REP are the within site replicate effects fitted as a fixed factor; FAM(SITE) are the within site family effects fitted as a random factor; FAM are the across site family effects fitted as a random factor; FAM.SITE are the site by family interaction effects fitted as a random factor; and ε is a vector of residuals for each trait. For model 1, full inter-trait and inter-site variance and covariance matrices were fitted for the family and residual effects. For model 2, the model terms FAM and **e** included an inter-trait variance and covariance matrix pooled across sites.

Heritabilities, genetic correlations, site means and all standard errors were calculated by ASREML. Heritabilities for the individual site and multisite analyses were calculated as shown in models 3 and 4 respectively.

$$h^2 = \sigma_f^2 / r(\sigma_f^2 + \sigma_e^2) \quad [3]$$

$$h^2 = \sigma_f^2 / r(\sigma_f^2 + \sigma_{f.s}^2 + \sigma_e^2) \quad [4]$$

Where h^2 is the narrow sense heritability; σ_f^2,$\sigma_{f.s}^2$ and σ_e^2 are, respectively, the variance components for FAM, FAM.SITE and ε estimated in the models above; and r is the coefficient of relationship. The coefficient of relationship used was 0.4 which assumes a selfing rate of approximately 30% (GRIFFIN & COTTERILL 1988).

Estimation of genetic gains

Genetic gains for diameter, basic density, cellulose, collapse and appearance board grades were estimated under five different selection strategies. This was done in a three-step process. Firstly, individual tree breeding values were calculated for diameter, basic density, cellulose and collapse. Secondly, for five selection strategies, individual tree index values were calculated, a population was selected, and the average breeding values of the selected population calculated. And thirdly, the assortment of appearance board grades was estimated using breeding values for collapse.

Calculation of breeding values

Individual tree breeding values were calculated by fitting the following multivariate model using ASREML:

$$Y = \mu + SITE + REP + TREE + FAM.SITE + \varepsilon \quad [5]$$

Where Y, μ, SITE, REP, FAM.SITE and **e** are as previously defined and TREE are the individual tree breeding values (additive genetic) for diameter, basic density, cellulose and collapse. The terms TREE and ε included inter-trait variance and covariance matrices pooled across sites. Correlations were fixed to values calculated in model 2 and a coefficient of relationship of 0.4 was assumed for calculating additive variances.

Selection of trees and estimation of gains

Five selection strategies were evaluated with each strategy applying different sets of economic weights to the traits (Table 3). The weights describe the relative importance of a standard deviation unit of that trait. The growth index (1) simply maximises volume per ha. The wood chip index (2) maximises profit per hectare from wood chip production. Index values were based on those of BORRALHO *et al.* (1993) with weights converted to standard deviation units. The kraft pulp index (3) maximises profit per hectare for unbleached kraft pulp production. Index values are taken from GREAVES *et al.* (1997) and these also have been converted to units of standard deviation. The collapse index (4) minimises collapse, or maximises recovery of high grade appearance timber. The appearance sawlog index (5) represents an index that maximises profit per ha when selling appearance grade products and places equal weights

Table 3. Economic weights of stem diameter (D), basic density (BD), cellulose content (CEL) and collapse (COL) expressed in standard deviation units for each selection index.

Index	D	BD	CEL	COL
1. Growth	1	0	0	0
2. Wood chip	1	1	0	0
3. Kraft pulp	3	3	1	0
4. Collapse	0	0	0	1
5. Appearance sawlog	3	0	0	2

on maximising volume and minimising collapse. For this index, weights are not true economic weights because no economic information has been used – they are estimates used to demonstrate, in simple terms, the effect of using collapse as part of multi-trait selection.

For each selection strategy individual tree index values were calculated as:

$$I = BV_D.W_D / \sigma_D + BV_{BD}.W_{BD} / \sigma_{BD} + BV_{CEL}.W_{CEL} / \sigma_{CEL} + BV_{COL}.W_{COL} / \sigma_{COL} \quad [6]$$

Where ***I*** is a unitless index value, BV is the breeding value for each trait (see Table 2 for definition of subscripts), s is the additive genetic standard deviation for these traits; and W is the arbitrary economic weight for each trait. The economic weights used for each index are shown in Table 3.

The top 60 trees were 'selected' for each selection strategy and then the average breeding values for diameter, basic density, cellulose, and collapse were calculated. These were then expressed as a percentage change from the unselected population. The selected population consisted of 60 trees from a population of 1160, or 5 %. This approximated the intensity of selection required for a clonal seed orchard where 20 clones are required with the restriction that no family is represented by more than two individuals.

Estimation of board grades

The assortment of appearance grade board grades was estimated for each selection strategy. After knots, checking has been identified as the major source of appearance product degrade in 25 year old *E. nitens* and other factors, such as kino and splitting, appear insignificant (WAUGH & YANG 1994). Since pruning is standard practice for *E. nitens* sawlog plantations (NEILSEN & PINKARD 2000) knots are not a factor and, in this analysis, it is assumed checking is the primary factor determining board grade. Therefore checking was used to predict board grade and this was done in a two-step process. Firstly, checking was predicted from collapse; and secondly, board grades were predicted using these values for checking.

Breeding values for checking were predicted as follows:

$$BV_{CHECK} = BV_{COL} \cdot r_g \quad [7]$$

Where BV_{CHECK} is the individual tree breeding value for board checking in units of genetic standard deviation; BV_{COL} is the breeding value for collapse measured on core samples, also in units of genetic standard deviation; and r_g is the genetic correlation between board checking and core collapse. BV_{COL} was calculated using model 5. The genetic correlation between board checking and core collapse is unknown but was assumed to be 0.7 for this analysis. By assuming this imperfect correlation it is recognised that collapse will not explain all variation in checking.

Board grades were defined according to the

Table 4. Definitions of appearance board grades.

Board grade[1]	Surface checks[1] ($mm \cdot m^{-2}$)	Internal checks[1] (no. per 0.005 m^2)	No. boards in grade[2] (%)	Range[3] (SD units)
1. Joinery	250	1	40	<-0.25
2. Select	300	1	26	–0.25 to 0.41
3. Standard	1000	3	14	0.41 to 0.84
4. Utility	2000	6	20	>0.84

[1)] Board grades and definitions of checking after WAUGH and ROZA (1991).
[2)] Percentage of product out-turn measured by WAUGH and YANG (1994) for 25 year old Tasmanian *E. nitens*.
[3)] Taken from table of cumulative probabilities of the standard normal distribution. For example, for joinery grade Pr ($z < -0.25$) = 40 %.

groupings shown in Table 4. This grading system was used by WAUGH & YANG (1994) to grade plantation grown *E. nitens* in a Tasmanian saw milling study. The percentages of product out-turn for each grade, which is also shown in Table 4, are the out-turns estimated by WAUGH & YANG (1994) assuming branches have been removed. This grading system was developed by WAUGH & ROZA (1991) as a visual grading system for young native forest eucalypts. It grades on 10 criteria, which include surface checks, internal checks, green knots, holes, kino, spring /bow, sapwood and end splits. However, for reasons discussed above, only surface checks and internal checks were used to define board grades in this current study. The product out-turns shown in Table 4 are used to describe the 'baseline' and it is assumed this data represents a typical rotation age *E. nitens* pruned plantation.

Board grades were defined in standard deviation units using the frequencies in each grade given by WAUGH & YANG (1994). The range of values appropriate for those frequencies were taken from a table of the cumulative probability of the standard normal distribution, and these are shown in Table 4. Values for BV_{CHECK} (calculated in equation 7) were then converted to a board grade and, for each selection strategy, the frequency distribution calculated.

RESULTS

Site differences

There were statistically significant differences between sites for all traits (Table 5). Growth rates on all sites were good and total volumes were predicted using Farm Forestry Toolbox (Private Forests Tasmania 2001) to be 235, 226 and 268 $m^3 \cdot ha^{-1} year^{-1}$ for Dial, Gog and Kamona respectively. Basic density and cellulose content were highest at Gog, and collapse at this site was lowest. For basic density and cellulose, differences between Gog and other sites were about 4 to 5% but for collapse the differences were about 20%.

Table 5. Least square trait means (± standard error) for stem diameter (D), basic density (BD), cellulose content (CEL) and collapse (COL).

Trait	Dial	Gog	Kamona
D (cm)	18.4±1.0	20.8±1.0	23.6±1.14
BD (kg m^{-3})	441±5	470±6	450±5
CEL (%)	40.3±0.3	43.0±0.3	41.3±0.2
COL (%)	18.6±1.7	13.4±1.7	16.5±1.7

Heritabilities

Heritabilities for each site and for a combined site analysis are shown in Table 6. In a combined site analysis, all traits had heritabilities that were moderately high (ranging from 0.40 to 0.56) and for all traits except diameter heritabilities were statistically significant between sites. Basic density and cellulose content had very high heritabilities on some sites (Gog and Kamona) and, on these sites, it appears most variation is explained by additive genetic variance.

Table 6. Heritabilities (± standard error) for stem diameter (D), basic density (BD), cellulose content (CEL) and collapse (COL).

Trait	Dial	Gog	Kamona	All sites
D	0.37±0.12	0.45±0.13	0.32±0.12	0.40±0.10
BD	0.50±0.16	0.96±0.18	0.63±0.17	0.53±0.13
CEL	0.52±0.21	0.86±0.20	1.05±0.21	0.56±0.15
COL	0.23±0.11	0.48±0.15	0.61±0.17	0.38±0.10

Correlations

Genetic correlations for the combined site analysis are shown in Table 7. Favourable and strong genetic correlations occurred between diameter and cellulose and between basic density and collapse, and these were stable across sites. Adverse and moderately strong correlations occurred between diameter and basic density, diameter and collapse, basic density and cellulose, and between cellulose and collapse. Correlations between diameter and col-

Table 7. Genetic correlations (r_G) with standard errors above diagonal and phenotypic correlations (r) below diagonal for stem diameter (D), basic density (BD), cellulose content (CEL) and collapse (COL).

	D	BD	CEL	COL
D		−0.57±0.15	0.79±0.10	0.75±0.10
BD	−0.11		−0.45±0.18	−0.75±0.11
CEL	0.32**	0.11*		0.54±0.16
COL	0.47**	−0.36**	−0.02	

* Significantly different from zero at $p < 0.05$.
** Significantly different from zero at $p < 0.01$.

lapse, basic density and collapse and between diameter and cellulose were stable across sites, but for all others site variation was significant. For example, genetic correlations for cellulose and collapse varied between 0.21 and 0.85 and genetic correlations between diameter and basic density varied from between –0.16 and –0.77.

Phenotypic correlations between traits are shown in Table 7. Correlations between most traits were either weak or not significantly different from zero. Correlations were also measured separately for each site, but these were essentially the same as for the combined site data shown in Table 7. The strongest correlations were those for collapse with diameter (r = 0.47) and for collapse with basic density (r = –0.36). More variation in collapse was explained using a multivariate relationship where diameter and basic density were the predictive variables (r = 0.56), although this relationship still only explained 31 % of total variation and therefore appears of limited practical value.

Genetic and phenotypic correlations between collapse and wood density measured using x-rays techniques are shown in Table 8. It is thought that collapse may be influenced by low earlywood density or high differences between earlywood and latewood density rather than density averaged across growth rings (CHAFE *et al.* 1992; YANG 1996). However, in this study these measures of density were not better predictors of collapse. Correlations between collapse and the minimum density within a ring at each age were lower than to those calculated using bark to bark averages (compare Tables 7 and 8) and correlations between collapse and the density differential within a ring were significantly lower than for other measures of density.

Table 8. Genotypic correlations (r_G) and phenotypic correlations (r) between collapse and wood density measured by x-rays.

Age	Density measure	r_G ± se	r^1
6	Average	–0.57±0.21	–0.25**
	Minimum	–0.28±0.25	–0.19**
	Differential	–0.33±0.25	–0.14**
8	Average	–0.58±0.19	–0.32**
	Minimum	–0.57±0.22	–0.22**
	Differential	–0.24±0.28	–0.18**
10	Average	–0.61±0.19	–0.28**
	Minimum	–0.63±0.21	–0.19**
	Differential	–	–0.09*

[1] r values marked ** are significantly different from zero at P<0.01 and those marked * are significant at p < 0.05.

[2] r_G could not be measured because genetic variation was close to zero.

Genotype by environment interaction

No genotype by environment interaction was present for diameter and collapse. For these traits family by site variance was zero (Table 9) and genetic correlations between sites were very high (Table 10). Genotype by environment interactions for basic density and cellulose content were significant but relatively small. Family by site variance contributed about 5 % of total variance for these traits (Table 9) and genetic correlations between sites ranged between 0.67 and 0.92 (Table 10). However, for both these traits the interactions appear of no practical significance. Basic density interactions appear caused by minor rank changes in many families and no families had large differences in ranking between sites. Excluding the most interactive families did not substantially alter the size of interactions. Cellulose content interactions appear to be caused by scale effects. This occurs where genetic expression on one site is much stronger than other sites. After weighting cellulose data by the site standard deviation, family by site variance was less than 1%.

Genetic gains

The target criterion for appearance grade products is assumed to be select grade or better, and the percentage of product meeting this board grade is predicted to change substantially under different selection strategies (Table 11). The worst selection strategy is to select for diameter alone. This strategy would result in a substantial drop in wood quality, with only 8 % of boards making select grade or better. Selecting on a wood chip index (i.e. diameter and basic density) appears to maintain appearance grade wood quality at its current level, and achieve gains in growth and basic density. Selecting on a kraft pulp index gives a similar result, with similar proportions of boards making select grade or better. However, under this selection strategy it appears that the board recovery for the highest grades will reduce.

Good genetic gains in reducing the effects of collapse can be made when selecting directly for this

Table 9. Variance components and heritabilities (± standard error) of stem diameter (D), basic density (BD), cellulose content (CEL) and collapse (COL) for the combined site analysis.

Trait	σ^2 family	σ^2 family.site[1]	σ^2 error	h^2
D (cm)	5.7±1.6	0±0	29.9±1.3	0.40±0.10
BD (kg m^{-3})	200±61	59±24	673±36	0.53±0.13
CEL (% kg kg^{-1})	0.38±0.11	0.01±0.04	1.22±0.09	0.56±0.15
COL (%)	7.0±2.1	0±0	39.2±2.1	0.38±0.10

[1)] ASREML calculated small negative family by site variances for D and COL and therefore the analysis was redone with these values fixed to zero.

Table 10. Genetic correlations (± standard error) between sites for stem diameter (D), basic density (BD), cellulose content (CEL) and collapse (COL).

Trait	Dial & Gog	Dial & Kamona	Gog & Kamona
D	1.09±0.10	0.93±0.13	1.14±0.12
BD	0.73±0.15	0.67±0.19	0.92±0.11
CEL	0.77±0.23	0.91±0.19	0.89±0.15
COL	1.01±0.18	1.00±0.25	0.98±0.16

trait alone (Table 11) with a 35% decrease in the amount of collapse predicted. This is expected to result in all boards meeting the top appearance grade. However, these gains come with a large sacrifice in growth, with an 18 % fall in diameter being predicted. Reasonable improvements in both growth and collapse can be obtained using the appearance sawlog index, which selects for both diameter and collapse. Predicted improvements are a 9 % gain in growth and a 7 % reduction in collapse (Table 11). Importantly, this gain in collapse is predicted to give a substantial improvement in appearance grade board quality, with 93 % of boards predicted to make select grade or better.

DISCUSSION

Collapse and checking are fundamental problems for the production of sawn timber for many eucalypt species (JACOBS 1979) and it appears that *E. nitens* is a species susceptible to checking (WAUGH & YANG 1994; MCKENZIE *et al.* 2003a). In addition, there is evidence that some sites will express this problem more severely than other sites (SHELBOURNE *et al.* 2002). Checking appears to be more severe in the high value lower pruned log (RAYMOND & SAVAGE, unpublished data) and thus is likely to have a severe impact on the economics of growing for appearance products. The silvicultural regime required for sawlog production (ie. prune, thin and grow for a longer rotation) is a high cost regime and is dependent on high product prices to be profitable. If checking is a major cause of downgrade in end product quality, as it appears from the grading system defined by WAUGH & ROZA (1991), then inclusion of this trait into *E. nitens* breeding programs would be a priority.

This study indicates that tree breeding can be used as a tool to manage collapse and checking. However, before a breeding plan can be implemented there are two questions to be answered. These are; firstly, 'what is the best selection trait?' and secondly, 'what economic weight do you apply?'

Selection traits

An essential criterion for a selection trait is that it be correlated with the breeding objective trait. In this study, it has been assumed that tangential collapse of a wood core (the selection trait) is moderately correlated (r_g = 0.7) with board checking (the objective trait). There are two aspects to this assumption. The first is that collapse of a core is related to collapse of the pruned (or lower) log and a study by RAYMOND and SAVAGE (unpublished data) suggests that for both *E. nitens* and *E. globulus* this is a valid assumption. The second is that collapse is related to checking. For eucalypts in general it is known that collapse is a major cause of checking but not the only cause; some checking can be attributed to other factors such as tension wood (HILLIS 1978; JACOBS 1979; CHAFE *et al.* 1992). In this study it has been assumed that most checking in *E. nitens* is caused by collapse, but an allowance for other factors was made by using an imperfect genetic correlation between collapse and board checking (r_g = 0.7). The assumption that collapse is the main cause is supported by the study of MCKENZIE *et al.* (2003b), where tangential collapse measured on *E. nitens* discs was well correlated with checking on butt log boards (r = 0.73), and also by the study of ILIC (1999) where collapse measured on *E. regnans* boards was correlated with checking measured on the same boards (r = 0.68). Importantly, this latter study noted that low levels of collapse were always associated with low numbers of checks.

Another important criterion for a selection trait is that it can be assessed in a cheap and non-destructive fashion. Measuring tangential collapse on a wood core meets this standard. If cores are already being taken for basic density sampling, then the cost will be less than AUD 0.50 per tree and including this assessment in a breeding program could be done with only a 5 % increase in the basic density sampling cost. The method is also very simple. The major potential cause of inconsistent results is non-uniform drying and this can happen if cores are allowed to begin drying at room temperature before being put into the oven. The problem can be avoided by ensuring cores are always oven dried from the saturated state. Other traits, such as density variation or minimum density, have been suggested as selection traits for collapse (CHAFE *et al.* 1992; Yang 1996) but these are more expensive to measure and imperfect predictors. Collapse is caused by thin cell walls and presumably measurements of density, even very specific measures, are not perfect measures of this property.

Economic weights for appearance sawlogs

A fundamental question to a forest grower planning to sell appearance grade products is: 'how should selections be made?' The importance of this question cannot be overstated because of the high cost silvicultural regime required. The wrong tree breeding decisions may result in wood quality being unsuitable for the appearance grade market and this may jeopardise the profitability of these plantations.

Decisions about the best weights for traits to maximise profitability and are usually made based on an economic evaluation involving market prices and a quantification of the importance of each trait in the production process. This has been done for kraft pulp production (eg. BORRALHO *et al.* 1993; GREAVES *et al.* 1997) and these examples are good case studies for the methodology. However, for the production of appearance grade timber this has not been done and cannot be done at present because the industry is 'young', markets for this wood are not established, and therefore there are no strong 'market signals' to forest growers. Furthermore, these types of decisions are complex for solid wood growers because they are usually intending to produce a range of potential products from the same trees. It is important that decisions that aim to improve the quality of appearance products do not lead to a degradation of product quality for alternative markets, particularly for wood chips and pulp production, where there are established markets. Therefore in this analysis some typical industry indices were evaluated and are compared to a 'best guess' appearance grade sawlog index.

An important finding of this study is that appearance grade wood quality is predicted to decline markedly when selecting for growth alone. This would virtually exclude the possibility of selling logs to the joinery market. Under this strategy, plantations that had been silviculturally managed to produce for this market (i.e. pruned, thinned and grown on a 20 year rotation) would probably make a financial loss, despite genetic gains in growth. This is because high product prices are necessary to pay for the investment in such regimes (see CANDY & GERRAND 1997).

Selecting on a wood chip index or kraft pulp index appears to be a suitable selection strategy if appearance grade wood quality is currently adequate. Checking does not appear to get any worse and gains are made in growth and basic density. Therefore, this strategy would provide increased profitability through decreased growing costs (ie. improved productivity) and increased value for the sale of wood chips without excluding the appearance grade market.

Selecting only to reduce collapse would probably be an uneconomic proposition for a forest grower under present cost structures. Although big reductions are predicted for checking, it comes at a high cost in terms of growth rate. An 18 % drop in diameter would result in a site that previously had a productivity of, say, 25 $m^3 \cdot ha^{-1} \cdot year^{-1}$ falling to less than 20 $m^3 \cdot ha^{-1} \cdot year^{-1}$. Site productivity is the most sensitive variable to eucalypt sawlog plantation profitability and, in a study in Tasmania, sawlog plantations were uneconomic when site productivity was low (CANDY & GERRAND 1997). In addition, selecting in this way would increase the growing cost of wood and limit options for selling other products. Therefore, this is not a selection strategy that a grower would be likely to adopt.

Reasonable improvements in growth and reductions in the amount of checking can be obtained simultaneously using an appearance sawlog index. Importantly, the shift in checking under this strategy is predicted to be adequate to ensure most boards meet the standards for the joinery market (that is select grade or better) and this may make *E. nitens* well suited for the production of appearance grade products over a wide range of sites. This strategy also provides reasonable gains in pulpwood quality (basic density and cellulose content) and therefore does not appear to exclude the sale of other products from the same trees. Selecting for collapse appears to give much better improvements in appearance board quality than when selecting simply for basic density. Therefore sawlog growers should select directly for this trait rather than assuming that selecting for basic density will be suitable.

CONCLUSION

Collapse is a trait that should be included in breeding programs if logs are to be sold for appearance grade products. Collapse is under moderate to high genetic control and is not influenced by genotype by site interactions. It has strong and favourable genetic correlations with basic density but strong and adverse correlations with diameter growth. Tangential collapse can be measured on 12 mm increment cores easily and at low cost. If basic density is being measured, collapse can be included as a part of breeding programs at very little additional cost.

The percentage of product in different appearance board grades is predicted to change substantially with different selection strategies. If selecting for diameter alone, a large increase in checking is predicted and very few boards are expected to be acceptable for the joinery market. Selecting on a 'wood chip' or 'kraft pulp' index is expected to cause minimal changes in checking and therefore this is a reasonable option if current wood quality is acceptable for the appearance grade market. If it is required to lower the incidence of checking, and evidence from other studies suggests this will be the case, then an index including diameter and collapse is recommended. Selecting in this way is predicted to improve growth and decrease the incidence of checking to a point where most boards will be suitable for the joinery market.

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