The effect of growth strain and other defects on the sawn timber quality of 10-year-old *Eucalyptus globulus* Labill.

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Summary

Fifty-nine trees were sampled from three provenances of *Eucalyptus globulus* Labill. in 10-year-old plantations at two separate sites. The butt logs were selected as the study sawlogs. Growth strain was measured at three heights along the log length and three circumferential positions at each height. The logs were sawn and graded before and after seasoning to appearance grade. The impact of each grade-limiting defect on the result was examined. Particular attention was given to the effect of growth strain on the percentage of sawn boards that exceeded the permissible distortion limits of Australian standard AS2796.1 as feedstock. The logs were from young, small-diameter, unpruned trees; knots and pith were the primary grade-limiting defects. Average growth strain of the sawlogs and the tree diameter at breast height in combination accounted for 42% of the total variation in the percentage of excessively distorted boards. Density had no direct causal effect on this percentage, but had an indirect effect through its significant correlation with growth strain.

Keywords: growth stress, wood properties, wood defects, sawnwood, *Eucalyptus globulus*

Introduction

Eucalyptus globulus Labill. is one of the most widely-planted hardwood species in the world, primarily because of its superb growth rate and high quality pulpwood. It is the most extensively planted eucalypt in Australia — approximately 311 600 ha to September 2000 (Wood *et al*. 2001). The Green Triangle Region of South Australia and Victoria has seen a rapid expansion in the area of *E. globulus* in the last three years. Within this region, a substantial portion of the blue gum plantations is more than 150 km from the international port at Portland; a distance beyond which it is currently considered uneconomic to transport woodchips. In addition, over 70% of the area planted with blue gum within the economic transport zone is not under contract for sale as woodchips. The development of higher value uses for this timber would therefore be of considerable economic benefit to the region.

One of the key factors limiting the use of young plantation-grown eucalypts as sawlogs is high growth stress within the timber (Malan 1995, 1997; Waugh 1998a, 2000; Garcia 1999; Maree and Malan 2000). The continuous development of growth stress in newly formed wood during cell maturation results in a gradient of residual stress across tree stems during tree growth. When the logs are sawn, distortion and sawing inaccuracy may occur in the sawn timber due to the release and consequent re-balancing of the residual stress. This can be a major problem in the conversion of high-stress and small-diameter logs. Attempts to understand the effect of growth stresses on sawn timber distortion, and quantify their impact, have been made from both scientific and utilization perspectives (Jacobs 1938, 1939, 1945; Boyd 1950; Kubler 1959, 1987; Hall 1965; Okuyama and Sasaki 1979; Page 1984; Gerard 1994; Malan 1997; Waugh 1998a, 1998b, 2000; Muneri *et al.* 1999). Australian experience with regrowth eucalypts (average dbh 500–600 mm, 50–90 years of age) indicates that when peripheral growth strain in logs is below 800 μm[1], sawn product distortion becomes acceptable, provided that adequate sawing strategy and sawing facilities are used (Waugh 2000). Quantitative information on the impact of growth stress on distortion of timber sawn from young, small-diameter, plantation-grown *E. globulus* is scarce, despite distortion having been noted in a number of sawing trials or related studies (Thomson and Hanks 1990; Brennan *et al.* 1992; Waugh and Yang 1993; Moore *et al.* 1996; Northway and Blakemore 1996; Yang and Waugh 1996).

A comprehensive study has been in progress to investigate the relative importance of genetic and growth conditions on some basic wood properties in 59 ten-year-old *E. globulus* trees from three provenances. The properties and factors examined include growth strain, density, microfibril angle and shrinkage, the relationships between these properties, and their impact on the sawn timber quality. Results on growth strain variation between provenance and sites, and within trees, have been published (Yang and Fife 2000; Yang *et al.* 2001). The present paper examines the major causes of degrade in boards sawn from young plantation-grown *E. globulus*, and the extent to which growth strain, growth

[1] 1μm equals 0.000001

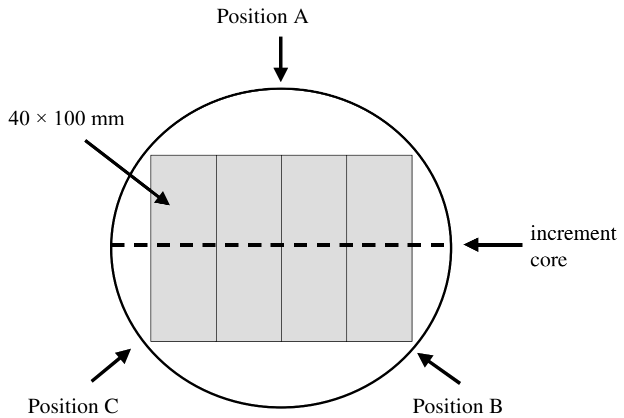

Figure 1. The ideal location of the study boards

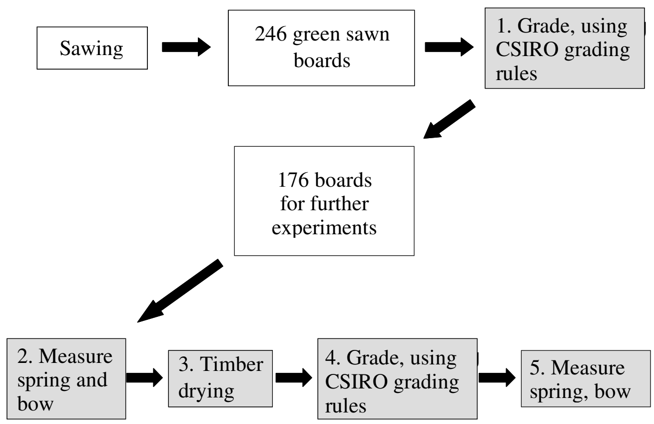

Figure 2. Flow chart of sawing, timber drying and various types of measurement at different stages

rate (dbh) and density explain the proportion of rejected boards. Growth strain or growth stress refers solely to the longitudinal growth strain or longitudinal growth stress except where specified. Relationships between growth strain and sawn timber distortion will be reported in a separate paper.

Material and methods

Material

Fifty-nine trees of 10-year-old *E. globulus* were sampled from three provenances grown at two separate sites near Mt Gambier, South Australia. Butt logs were selected as the study sawlogs. Growth strain was measured at three heights along the log length and three circumferential positions at each height. Detailed description of growth strain measurements in both the standing trees and sawlogs (butt logs), log sawing, and measurement of sawn timber distortion can be found in Yang and Fife (2000) and Yang *et al.* (2001). To be consistent, the same abbreviations as in those two papers are used in this paper to designate the six tree groups. HJ, HK, and HT respectively refer to Jeeralang, King Island, and SE Tasmania provenances at Heath Block[2]; JJ, JK, and JT respectively refer to Jeeralang, King Island, and SE Tasmania provenances at Johnstons Block.

Prior to sawing, four radii of different colours were painted on the large end of each log, at right angles to one another, for board identification purposes. Surface defects of the logs were recorded and log sweep was measured.

The logs were back-sawn at the Victorian Timber Industry Training Centre mill at Creswick, Victoria. The sawyer aimed at maximum grade recovery using a sawing strategy implemented at the sawmill. The only restraint the sawyer was under was to cut as many 40 × 100 mm boards as possible along the same diametrical directions as those of the 12 mm increment cores taken prior to felling (Fig. 1). This sawing strategy yielded 202, 38 and 6 boards respectively in 40 × 100 mm, 25 × 100 mm and 20 × 100 mm cross sections. All the boards were 3.6 m long, except for ten that were 3.0 m or 2.4 m because of taper or excessive end defects in the boards. A flowchart (Fig. 2) summarizes the various processes the sawn boards went through. The shaded numbered boxes in the chart describe in sequence the measurements or treatments applied to the boards.

[2] Since there was no replicate at the sites, we used site and block interchangeably.

Table 1. Various grades in the CSIRO grading rules and AS2796.2

CSIRO grading rules		AS2796.2
Grade number	Grade	
Grade 1	Moulding grade	Select grade
Grade 2	Polishing grade	Select grade
Grade 3	Select grade	Medium Feature grade
Grade 4	Standard grade	Medium Feature grade
Grade 5	Utility grade	Medium Feature grade
Grade 6	Cover grade	High Feature grade
Grade 7	Case grade	High Feature grade
	Reject	

Grading boards before and after drying using CSIRO grading rules

All the boards were graded off the green chain for pith (or pith material), knots, wane, kino, decay and insect attack, using the CSIRO in-house grading rules (see Kerruish and Rawlins 1991, pp. 182–185) for appearance sawn products[3]. This set of rules classifies sawn products into more grades than the Australian standard AS2796.2 (1999). Each of these grades has a grade number, with a higher number representing a poorer grade (Table 1). Despite many differences in quantitative specifications between CSIRO's grade specifications and AS2796.2, an approximate comparison can still be made between the two (Table 1).

Only the boards whose location, conceptually, fitted those in Figure 1 (176 boards) were used for further experiments. Their bow and spring were measured six days after sawing. This period provided sufficient time for the growth-stress-related distortion to equilibrate in all sawn boards.

[3] The severity of certain types of defects such as knots and decay often remains unchanged before and after drying. Therefore, the grading rules for seasoned appearance products may be used to grade green boards for certain types of defects.

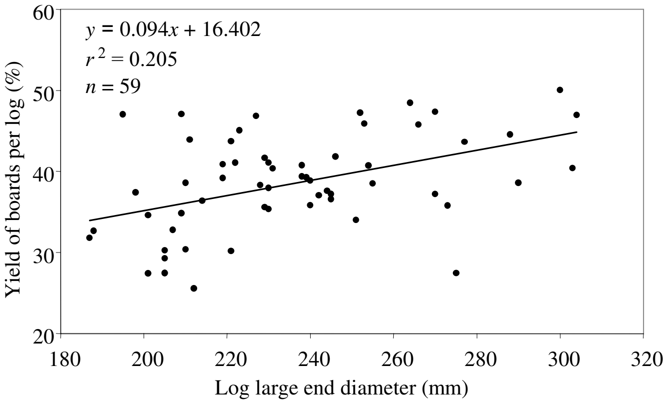

Figure 3. Relationship between log large end diameter and volume yield of green sawn boards

The study boards were stacked under weight and air-dried in a warehouse for 13 months. After that time, the average moisture content was about 18%. The final kiln drying involved reconditioning for 6–7 h, and then drying at conditions of 55°/40°C (dry bulb/wet bulb temperature) for 3 days, then at 70°/65°C for 3 days. After final drying, the boards were dressed to 35 × 90 mm in cross-section. They were then re-graded using the same CSIRO in-house grading rules for pith (or pith material), knots, wane, kino, decay, insect attack and surface checking. Spring and bow were measured on these seasoned boards.

Grading green boards for distortion, using AS2796.1

A particular emphasis in this study was to quantify the impact of distortion on sawn timber. For this reason, the green sawn boards were also graded for distortion only. Since the distortion limits in CSIRO's grading rules are for seasoned products, it was necessary to adopt the distortion limits of feedstock[4] of AS2796.1 (1999). For feedstock of 35 × 90 × 3600 mm, the respective limits on bow and spring in AS2796.1 are 30 mm and 45 mm. By interpolation, the respective limits on bow and spring for feedstock of 40 × 100 × 3600 mm were calculated as 26 mm and 42 mm. Thus, the green boards were graded against 26 mm for bow and 42 mm for spring. In the following text, the boards whose distortion had exceeded the permissible limits are referred to as excessively distorted boards.

For each log, the percentage of excessively distorted boards was determined. It is referred to as 'distortion grading results' in the following text.

Data analysis

An analysis of variance was carried out on the distortion grading results to test the significance of differences between sites and provenances and their interaction. Relationships between measured variables and their effect on the distortion grading results were examined using PATH analysis (EQS 5 for Windows software package by Multivariate Software Inc., USA). PATH analysis is a special use of multiple regression to help analyse the direct and indirect causal effects of independent variables and find the best regression model by elimination of variables that contribute little to the equation. PATH coefficients are standardized regression coefficients. In a PATH analysis diagram, single-headed arrows point from independent variables towards dependent variables and imply direct cause. Curved double-headed arrows connect independent variables and represent correlations. The PATH analysis output diagram shows PATH coefficients next to the single-headed arrows, correlation coefficients between independent variables next to the curved double-headed arrows, the coefficient of determination from the multiple regression, and the residual variance.

Results

Log size, sweep and volume yield of green sawn boards

The relationship between log size and volume yield of green boards is illustrated in Figure 3. Calculation of the volume yield per log was based on the actual dimensions of individual sawn boards. The relationship is significant ($P < 0.05$) with larger logs yielding a greater volume of sawn boards.

The largest sweep found in this study was 60 mm. The data indicated that the impact of sweep on volume yield is affected by log diameter and the way logs are sawn. The impact of sweep became obvious for smaller logs (e.g. 230 mm in diameter) and/or if the direction of sweep was at right angles to the saw plane in back-sawing. It decreased with increasing log diameter.

Effect of grade-limiting defects on the grade of green boards

The degree of downgrade is determined by the type and severity of defects, and can be arbitrarily quantified by the final grade of the sawn boards. The grade recovery is concerned with the relative yield of sawn boards in various grades.

The terminology 'inherent defects' and 'non-inherent defects' may be used at various places in the following text to refer to various defects. Pith, knots, kino and board distortion (as a result of growth stress re-balance) are the 'inherent' features of trees, and so 'inherent defects'. Insect attack and decay are the consequences of external biological invasion and are 'non-inherent defects'.

As stated previously, CSIRO grading rules were used to grade for pith, knots, wane, kino, decay, insect attack and surface checks, whereas Standard AS2796.1 was used separately to grade only for distortion.

Overall grade and grade-limiting defects

The yield of sawn boards in Grade 5 and better was very low for every tree group (Fig. 4). When all the data were pooled, 42% of the boards were in Reject, 28% in Grade 7 and 25% in Grade 6, and the boards that reached Grade 5 and better constituted 5%. The degree of downgrade by each of the grade-limiting defects is discussed in more detail below.

[4] AS2796.1 defines feedstock as sawn and partially processed boards intended for further processing into sawn or milled products, and may be supplied at any moisture content.

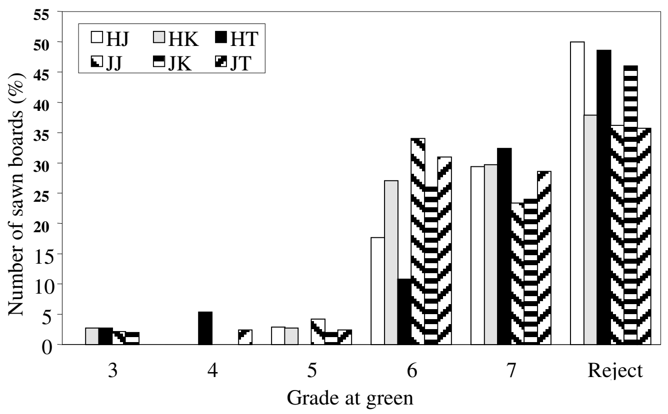

Figure 4. Final grade and the percentage of green sawn boards downgraded to each of these grades

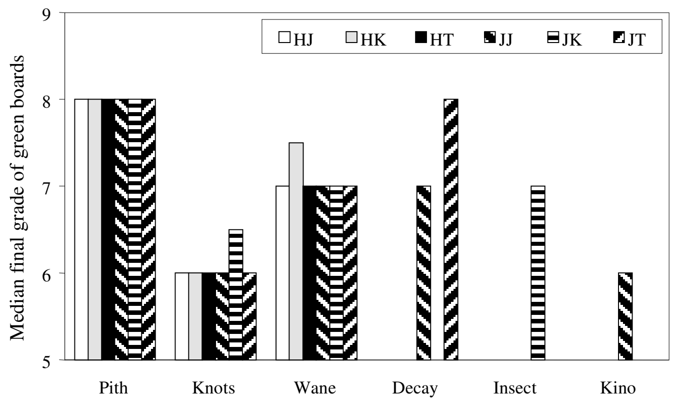

Figure 5. Median final grade of green boards and the causal grade-limiting defect. Reject is represented by Grade 8 due to graphing limitation.

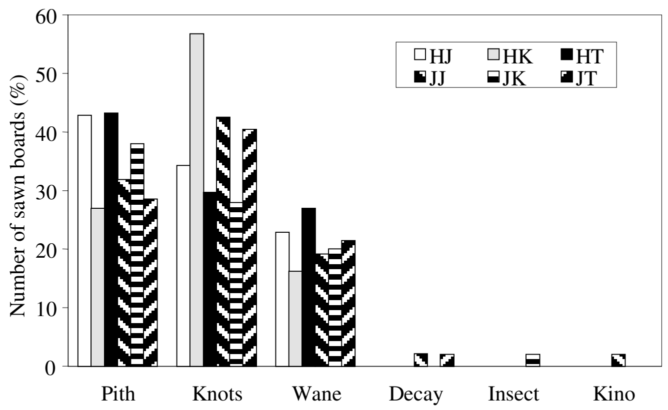

Figure 6. Grade-limiting defects and the percentage of green sawn boards downgraded by each of these defects

Pith

Due to small tree size (most were under 300 mm at breast height), a number of boards inevitably contained pith material. This situation was aggravated by the presence of wandering pith in many logs. With all the data pooled, the pith material downgraded the boards to Reject in most cases (Fig. 5), and was the grade-limiting defect for 35% of the boards (Fig. 6). This illustrates again the important association between large log diameter and good grade recovery. Trees will always contain the pith material, but obviously its effect diminishes in larger trees.

Knots

Dead knots downgrade sawn timber more than green knots of the same size class. For a given type of knot, the timber grade is normally determined by knot size and location, rather than its frequency. Since most knots in the study boards were green, the dead knots were combined with green knots, and simply called knots. With all the data pooled, knots downgraded the boards to Grade 6 or 7 in most cases (Fig. 5) and were the grade-limiting defect for 38% of the boards (Fig. 6). The least downgrade due to knots was Grade 3 or Grade 4, but such incidence was so rare that it occurred only once or twice in each tree group. Knots seemed to have a similar downgrading impact on all the tree groups, since the downgrade due to knots differed by only one grade between the tree groups (Fig. 5).

Wane

According to the CSIRO grading rules, sawn boards will not achieve Grade 4 and above if they contain wane in the best face. Where wane is allowed, its relative width and length determines its impact. In this study, wane downgraded the sawn boards to Grade 6 or 7 in most cases (Fig. 5), and was the grade-limiting defect for 21% of the boards (Fig. 6). Its downgrading impact was about the same across the tree groups. The causal effect of sweep and small log diameter on wane is commonly known and was discussed earlier. With larger and better-formed logs, the downgrading impact of wane should be greatly reduced.

Decay, insect attack and kino

Decay and insect attack occurred in all but one tree group. However, they were severe enough only in some of the Johnstons Block trees to surpass other common primary defects and become grade-limiting defects (Fig. 5). The affected boards were mostly from the mid-outer zone of the two largest logs and the logs whose diameters were well above the average dbh. Trees from Johnstons Block seemed more problematic in that their non-inherent defects were additional barriers in preventing sawn boards from reaching better grades (Fig. 5).

Fortunately, not many trees had been affected at Johnstons Block (severe insect attack in only one tree from King Island provenance, severe decay in one tree each from Jeeralang and SE Tasmania provenance, and severe kino in one tree from Jeeralang provenance). King Island and SE Tasmania provenances were virtually free of kino.

Impact of distortion on grade recovery, and relationship to growth strain

Bow ranged from 0 to 71 mm, with an average of 22 mm; spring ranged from 0 to 58 mm, with an average of 10 mm. Seventeen boards were free of bow, 31 boards free of spring, and 4 boards free of both bow and spring. The distortion grading result of each tree group is given in Table 2. Despite insignificant differences between sites and provenances (Table 3), overall the King Island provenance had a lower percentage of excessively distorted boards than the other two provenances, and as did Heath Block.

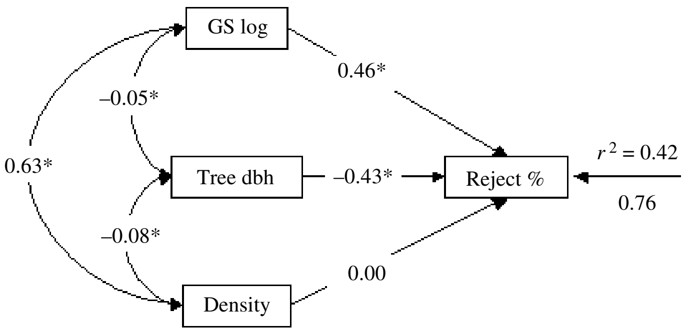

Figure 7. PATH analysis output diagram of the hypothesized effect of various variables on distortion grading results. 'GS log' = mean growth strain of sawlogs, 'Tree dbh' = diameter at breast height, 'Density' = mean density at breast height, and 'Reject %' = percentage of excessively distorted boards. Sample size = 59, Chi squared = 61.1.

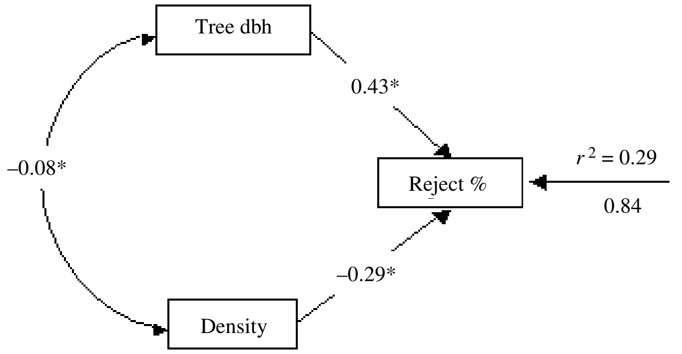

Figure 8. PATH analysis output diagram of hypothesized effect of tree dbh and mean density at breast height on distortion grading results. Sample size = 59, Chi squared = 20.6.

Table 2. Excessively distorted boards (%) graded for distortion only in green condition as feedstock of 40 × 100 × 3600 mm against AS2796.1

Statistics	Tree groups					
	HJ	HK	HT	JJ	JK	JT
Average	34.5	24.1	25.8	40.2	25.0	31.6
S.D.	19.5	9.7	22.0	15.1	19.3	29.7

Table 3. Analysis of variance on the percentage of excessively distorted boards

Source of variation	d.f.	Mean square	*F*	*P*
Site	1	251.01	0.61	0.44
Provenance	2	838.00	2.03	0.14
Interaction	2	37.13	0.09	0.91
Residual	53	412.63		

The output diagram of a PATH analysis on the hypothesized causal effect of three independent variables on the distortion grading results is shown in Figure 7. The PATH coefficients were significant for the path of 'GS log' (mean growth strain of sawlogs, 0.46) and 'Tree dbh' (–0.43), implying their significant direct causal effect on 'Reject %' (distortion grading results). The PATH coefficient for the path of 'Density' (density at breast height, 0.00) was insignificant and very low, implying density had little direct causal effect on the distortion grading results. The coefficient of determination (r^2) from this multiple regression model is 0.42.

The PATH analysis output diagram (Fig. 7) also shows significant correlations between all independent variables. Nevertheless, tree diameter had little relation with density and growth strain in logs, as indicated by the very low correlation coefficients (–0.05 and –0.08). The correlation between density and growth strain was at a modest level (r = 0.63). Through this correlation, density had an indirect effect on the distortion grading results, which can be quantified by multiplying the PATH coefficient of 'GS log' (0.46) with the correlation coefficient between 'Density' and 'GS log' (r = 0.63).

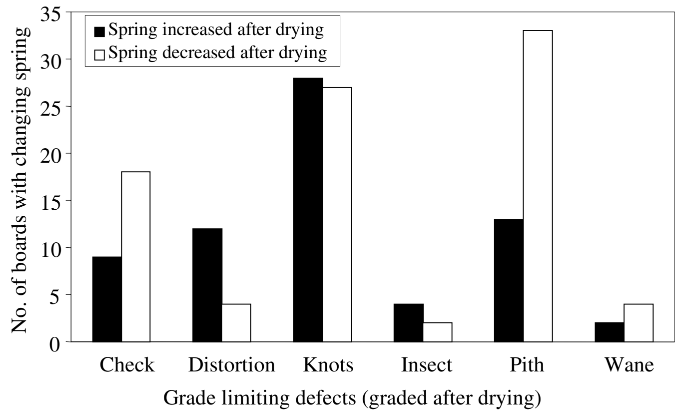

Figure 9. Number of boards whose spring had increased or decreased after drying, in correspondence to their grade-limiting defects

Growth strain in logs and tree dbh in combination explained 42% of the total variation in the distortion grading results, and their effect was at about the same level (Fig. 7). Where growth strain is not measured, density may be used to estimate the percentage of excessively distorted boards. However, its contribution to the coefficient of determination is quite small as found in this study (Fig. 8).

Change in grade and distortion after drying

As expected, the grade and grade-limiting defects changed after drying. Although pith and knots were still the primary grade-limiting defects, surface checking emerged as the third significant grade-limiting defect, and the worst checking always coincided with the pith. Comparison between grades before and after drying could not be made because of non-matching grading length (the grading length in many seasoned boards had been reduced in order to improve the grade).

Also, the spring had changed in about half of the boards after drying. The potential for spring to change, the way it changed (increasing or decreasing), and the magnitude of the changes depended on the types of the grade-limiting defects. Spring was more likely to change if the grade-limiting defects were knots and, to a lesser extent, pith. Spring was more likely to increase if distortion was the grade-limiting defect (Fig. 9). In other words, if sawn boards had severe spring to start with, the chances were that they would end up with worse spring after drying. Interestingly, the pith material appeared to have 'helped' reduce spring (Fig. 9). Spring was more likely to either increase or decrease at a greater absolute magnitude if the grade-limiting defect was distortion. Overall, spring decreased by approximately 10% after drying. Spring values before and after drying were positively correlated and the coefficient of determination was 0.42.

Bow was also significantly reduced after drying, as expected. On average, it was three times smaller than before drying. All except one board met the bow requirement in AS2796.1 for strip flooring products. This board had a very high bow before drying (65 mm) and retained a bow of 38 mm after drying.

Discussion

With all boards examined in this study, the major source of downgrade was the presence of pith, knots and wane when graded against CSIRO's grading specifications for appearance products. No significant effect of provenance or site, nor an interaction between the two was observed on the percentage of excessively distorted boards. The mean growth strain of the log, together with its diameter, explained 42% of the variance in the percentage of boards rejected. Density had an indirect effect on the distortion grading results.

The trees used in this study had not been grown for sawlogs. Knots in this circumstance became the worst primary grade-limiting defect for appearance grade and downgraded most sawn boards to cover or case grade. A similar result had been found in a study on young *E. globulus* by Thomson and Hanks (1990), although different grading rules were used. Knots can also be a primary grade-limiting defect for structural products from young *E. globulus*, but their presence did not necessarily lead to total product rejection (Thomson and Hanks 1990; Waugh and Yang 1993; Yang and Waugh 1996). Brennan *et al.* (1992) reported knots were a regular feature in sawn timber of young *E. globulus* but did not discuss their effect on the recovery and grade of the final products (VALWOOD®). A combination of genetic selection and silvicultural management can effectively control the type, size and frequency of knots, and also reduce the diameter of the knotty core. Harvesting at larger stem diameters also reduces the relative contribution of the knotty core. However, the economic feasibility of the above measures to improve grade recovery is a separate matter and must be examined carefully.

Pith downgraded both appearance and structural sawn products more severely than knots according to the grading standards or rules. In this study, pith was the second worst grade-limiting defect for appearance grade, primarily because of its wandering nature and the small diameter of logs. The effect of pith can be minimized through either harvesting trees at large diameters (this is true for wane as well), or by manufacturing products such as VALWOOD® that accept pith material (Brennan *et al.* 1992).

Severe bow (up to 71 mm) and spring (up to 58 mm) were found in 40 × 100 × 3600 mm sawn boards in this study. Distortion alone can cause a rejection of sawn boards as feedstock at up to 40%, as found in this study. The percentage of excessively distorted boards varied between tree groups, and was consistent with growth strain variation between tree groups (Yang and Fife 2000; Yang *et al*. 2001). This agrees with earlier observations that distortion in *E. globulus* varied from severe (Thomson and Hanks 1990; Waugh and Yang 1993; Yang and Waugh 1996) to mild (Brennan *et al.* 1992); those trees were from quite different areas and their genetic background, although not known, probably was also different.

Mean growth strain in logs and tree dbh together explained a significant percentage of excessively distorted boards as feedstock. This supports previous studies showing sawn timber distortion increases with increasing growth stresses and decreasing log diameter (Jacobs 1938; Boyd 1950; Kubler 1959; Malan 1997; Waugh 2000). To the best of our knowledge, no other studies have examined the effect of growth strain on sawn timber grades, so no comparisons can be made. Muneri *et al*. (1999) reported significant positive relationships between sawn board distortion and bow and spring. However, the implication or practical meaning of their actual growth strain measurements on the sawn timber recovery from those trees was not reported. Results from this study, however, directly quantify the importance of growth strain and log diameter to sawmills.

Density had no direct causal effect on the distortion grading result, but had an indirect effect through its significant correlation with growth strain. If density and growth strain are genetically correlated, selection for growth strain can be achieved through selection for density. Positive correlation between these two properties suggests that breeding for lower-growth-stress trees could result in lower density wood and probably also affect a few other wood properties. Caution, therefore, may be advised.

The poor volume and grade recovery found in this study should be considered in the light of the fact that the trees were not grown as sawlogs and were harvested at only 10 years of age. The underlying goal of the overall project was to compare provenances and effects of sites on sawlog potential.

Summary of results

- Pith, knots, and wane were primary grade-limiting defects, which is typical for young, small-diameter, unpruned logs.
- Insect attack and decay were more severe in trees from Johnstons Block and prevented affected boards from reaching a higher grade when other primary defects were less severe.
- Mean growth strain and tree dbh had a direct effect on the percentage of excessively distorted sawn boards and together explained 42% of its total variation.
- Density had no direct effect on the percentage of excessively distorted sawn boards, but had an indirect effect through its significant correlation with growth strain.
- Spring changed after drying. It was most likely to change if the grade-limiting defects were knots. However, it was most likely to increase, and to a greater magnitude, if sawn boards had severe distortion to start with.
- Bow was reduced by a factor of about three after drying. All boards except one met the bow requirement in AS2796.1 for strip flooring products.

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