Growth strain in three provenances of plantation-grown *Eucalyptus globulus* Labill.

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Revised manuscript received 9 October 2001

Summary

A comprehensive study was conducted on three provenances of ten-year-old *Eucalyptus globulus* grown on two sites near Mount Gambier, South Australia to assess wood properties as they relate to the end-use as sawn timber, and to examine differences in wood properties between provenances and sites. Ten trees with relatively good form and growth were selected from each provenance at each site. Growth strain was measured on both standing trees and the harvested logs.

Data analysis of longitudinal growth strain showed that: (1) mean growth strain throughout the stem at the first site (Johnstons Block) was higher in all three provenances than at the second site (Heath Block), in particular for SE Tasmania provenance; (2) King Island provenance had significantly lower growth strain than the Jeeralang and SE Tasmania provenances; (3) there were no significant differences in mean growth strain with sampling heights up the stem; (4) Jeeralang provenance had higher between-tree and within-tree variation in growth strain whereas King Island provenance had the lowest between-tree and within-tree variation; (5) a single measurement at breast height might be sufficient to detect large provenance differences for sample sizes of between ten and twenty trees per provenance, although much larger sample sizes would likely be required for detecting family differences; and (6) Jeeralang provenance, and SE Tasmania provenance at Johnstons Block, had high levels of growth strain, compared with other Australian major hardwood species, e.g. *E. regnans.*

Keywords: growth stress, wood properties, provenance, *Eucalyptus globulus*

Introduction

Forestry in South Australia has been dominated by plantations of radiata pine (*Pinus radiata* D. Don) since the turn of the 20th Century. This followed a series of species and provenance trials conducted in the early 1900s after which it was decided by the Forestry Board that the endemic eucalypt species had little potential to support a forest industry (Boardman 1988). Radiata pine out-performed the range of native and exotic species investigated.

No further detailed examination of the potential of eucalypt species for plantation forestry was undertaken until the late 1970s, when an experiment involving 36 species and 88 provenances of eucalypts was established at Mount Gambier in the south-east of South Australia (Cotterill *et al*. 1985). This experiment indicated that a number of eucalypt species could grow at satisfactory rates using prevailing silviculture which involved complete weed control to maximize water availability to the tree crop. One of the most promising eucalypts was Tasmanian blue gum (*Eucalyptus globulus* Labill.). Further examination of this species was undertaken as part of the National Afforestation Program (NAP) in 1988 with 114 ha being planted in South Australia to further examine potential in plantations (Woods and Forests 1989). In 1991, Apcel (now Kimberly Clark, Aust.) introduced a tree-planting program in south-eastern South Australia and south-western Victoria, the so called the Green Triangle Region (GTR), to encourage planting of up to 500 ha of blue gum annually with a view to supplying hardwood chips to its paper mill at Snuggery, SA (Woods and Forests 1990/91). Annual planting of blue gum increased rapidly during the late 1990s with 3380, 8000 and 20 000 ha planted in 1997, 1998 and 1999 respectively. This momentum was primarily driven by the Federal Government’s support for plantation forestry, the global woodchip market, and local farmers seeking better economic returns than those obtained from traditional agricultural pursuits.

Within the GTR a substantial area of blue gum plantations is further than 150 km from the international port of Portland, a distance beyond which it is currently considered uneconomic to transport woodchips. In addition, more than 70% of the area planted with blue gum within the economic transport zone is not under any contract for sale as woodchips. Development of alternative higher-value uses for this timber could be of economic benefit to individual farmers, and hence to the rural community as a whole, by increasing income and providing additional employment.

One of the key factors limiting use of young plantation-grown eucalypts as sawlogs is high growth stress within the timber. Growth stresses are self-generated in newly formed wood during cell maturation. The continuous formation of growth stresses during tree growth results in an uneven distribution of residual stresses across tree stems. When logs are sawn longitudinally, these residual stresses are largely released and the gradient of longitudinal residual stress causes sawing inaccuracy and sawn product distortion which, when severe, can alone result in downgrade, or rejection, of the sawn products (Jacobs 1938; Page 1984; Kubler 1987; Malan 1997; Muneri *et al*. 1999; Waugh 2000). Australian experience indicates that sawn-product distortion becomes acceptable only when growth strain in logs is below $8x10^{-4}$ (Waugh 2000). High growth stresses also cause log-end splits and a decrease in sawmill productivity. Growth stress is the product of growth strain and modulus of elasticity (MOE), both of which are obtained by measurements.

Earlier research has also shown that levels of longitudinal growth stress vary not only between and within species (Jacobs 1938; Waugh 1972; Nicholson *et al*. 1975; Malan and Toon 1978; Hillis 1984; Kubler 1987; Malan 1995; Okuyama 1997; Aggarwal *et al*. 1997, 1998; Wahyudi *et al*. 1999; Maree and Malan 2000) but are also highly responsive to growth conditions (Ferrand 1982; Kubler 1987, 1988; Wilkins and Kitahara 1991). From the tree growers'point of view, it is important to find and breed trees with low growth stress and to apply tree management strategies that help reduce, or do not promote, the development of high growth stress.

While severe end-splitting has been observed in plantation-grown *E. globulus* logs (Yang and Waugh 1996), no growth strain measurements have been made on this species in Australia, and there have been few reports on growth strain in this species grown elsewhere (Vignote *et al*. 1996).

This paper reports growth strain results from a study to determine the relative importance of genetic and environmental effects on growth strain in *E. globulus*, and to relate measured growth strains to sawn board distortion. In this paper, growth strain or growth stress refers solely to the longitudinal growth strain or growth stress except where specified. It reports growth strain results, as the MOE data are not yet available to calculate growth stress. However, the terminology of growth stress will occur in this paper when discussion involves results by researchers who reported only growth stress.

Material and methods

Materials

Two sites, planted in South Australia in 1988 as part of the NAP program, were selected. The 'Heath' is 25 km north-east of Mount Gambier. The site was flat with sand 50-90 cm deep over clay and described as a Young Sand (Stephens *et al*. 1941). 'Johnstons'at Glencoe is 22 km north-west of Mount Gambier. The site consists of low-undulating rises with a mosaic of soils, Mount Burr and Young Sands and Sandy Swamp soils (Stephens *et al*. 1941). Areas that were likely to be subjected to inundation were not planted. Elsewhere, due to the undulating nature of the terrain, the depth of sand varied from 1 m over clay to more than 2 m. The average annual rainfall, most of which falls in winter, is 680 mm at Heath (data from Auspine Mill at Tarpeena 5 km from Heath) and 860 mm at Glencoe (data from Forestry SA Glencoe nursery).

Site preparation at both sites involved strip cultivation with offset discs and mound ploughing with an interval of 4 m between the mounds. Weed control prior to planting was achieved with 3L Gesatop and 2L Roundup per hectare. Nine provenances of *E. globulus* were represented in the trials. Nine-month-old seedlings raised by Australian Paper Plantations' nursery in Gippsland (Vic.) were planted in July 1988 in unreplicated blocks of each provenance, each containing between 600 to 1000 trees with a distance of 2.4 m between seedlings along the mounds. Second-year weed control used 2L Verdict, 4L Lontrel and 8L Gestop per hectare.

Three provenances, Jeeralang, King Island and south-eastern Tasmania (SE Tasmania), were selected for this study to represent provenances from the wide range of environmental conditions in which *E. globulus* is found across Australia. Ten study trees were selected from each provenance at each site, giving six groups of trees (2 sites x 3 provenances) and 60 study trees in total. One study tree from King Island provenance at Heath Block was discarded later because of excessive stem decay.

The following abbreviations will be used to designate the 6 groups of trees: HJ, HK, and HT respectively represent Jeeralang, King Island, and SE Tasmania provenances at Heath Block; and JJ, JK, and JTrespectively represent Jeeralang, King Island, and SE Tasmania provenances at Johnstons Block.

Field measurements and tree selection

Field measurements and selection of the study trees were identical for each tree group.

Basal area growth was determined by measuring the DBHOB (diameter at breast height, nominally 1.3 m, over bark) of all trees growing within a randomly selected 12 x 20 m block. Ten trees with comparatively fast growth and better stem characteristics (straight, non-leaning, low taper, single stem, fewer large branches, fewer injuries, etc.) were selected as the study trees and their DBHOB measured. These trees were selected near each other to facilitate extraction of logs at harvest.

Growth strain was measured on the surface of each tree using a simplified Nicholson's (1971) method (Yang and Hunter 2000) at three circumferential locations at a nominal height of 1.3 m. These three locations were nominally equally-spaced, one facing the prevailing wind (A) which was determined by judging the direction of sweep in the tree. The exact direction of each position was measured using a compass. The respective average orientation for locations A, B and C was 224º, 105º and 350º at Heath Block, and 256º, 140º, and 29º at Johnstons Block.

After the study trees were felled, total tree height, height at lower crown, and the diameter of the tree stem at the lower crown were measured. One 6.2 m bushlog was removed commencing about 1.2 m from the butt of each tree stem. The ends of all bushlogs were sealed with wax emulsion log-end sealer as soon as they were cut, and colour-coded. Tags were attached to the large end of each bushlog and labels written on the log surface for identification. All the bushlogs were transported the next day to the Victorian Timber Industry Training Centre at Creswick, Victoria and stored under water spray.

Sawlog preparation and pre-sawing measurements were carried out six weeks after tree falling. The bushlogs were debarked and the end-splits on both ends recorded. Growth strain was

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[1] In an earlier paper (Yang and Fife 2000), the 4.3 m and 6.1 m heights were mistakenly reported as 3.7 m and 4.9 m.

measured on the bushlog surface at three heights, equivalent to 2.5 m, 4.3 m and 6.1[1]m above the ground on the tree before harvest. At each height, growth strain was measured at the same three directional positions as those measured on the tree before harvest. One 1.2 m billet was removed from the large end of each bushlog, followed by one 3.6 m sawlog and one 0.5 m billet. After the 3.6 m sawlog was removed, the radii corresponding to the growth strain measurement at the 1st and 3rd heights of the bushlog were identified on the ends of the sawlog, and measured.

Surface defects and sweep of the sawlogs were recorded. The logs were sawn to yield sawn timber of mostly 40 x 100 mm cross section. All the green sawn timber was graded according to appearance grade criteria[2] . The boards from the central cant were selected and their bow and spring measured. These boards were then stacked with weight restraint and the air-drying proceeded in a warehouse. Small specimens were prepared from the 1.2 m billets.

Results on the relationship between growth strain and other wood properties, and the effect of the level of growth strain on sawlog degrade and sawn board distortion will be reported separately.

Data analysis

Three analyses of variance were carried out. Firstly, mean values for strain for each tree were calculated and an analysis carried out to test the significance of differences between sites, provenances and the interaction. Secondly, the complete data set was analyzed to test for differences between trees in each provenance at each site and to test for sampling height differences. Thirdly, individual-tree data were analysed separately by height up the stem and sampling position around the stem. This was done to find the most accurate sampling position. The relationships of various tree dimensions to growth strain were examined.

Results and discussion

Tree growth and form

The areas of the stands used in this study represent a small portion of each site and have been selected to provide logs of 'sawable'size. Hence, they are not representative of the sites in general. The productivity of the stands can be gleaned from recovery data from recent harvesting operations yielding woodchips from each site. In 1997, about 12 ha of Heath was thinned at age nine years. This produced woodchips at a rate equivalent to an MAI of 30.3 m^3 y^{-1} (M. Underdown, Forestry SA, *pers. comm.*). Harvesting operations at Johnstons (at age 11 years) subsequent to removal of our study logs produced woodchips at a rate equivalent to an MAI of 24 m^3 y^{-1} (M. Underdown, Forestry SA, *pers. comm.*). These growth rates compare favourably with those reported from a range of sites in Western Australia by Hingston and Galbraith (1998) where MAIs ranged from 9.1 to 45.6 m^3 y^{-1}, with the site of 45.6 m^3 y^{-1} receiving a mean annual rainfall of in excess of 1400 mm (Hingston *et al*. 1998).

Growth, measured as DBHOB, differed considerably between the three provenances in the study areas (Table 1), and the ranking of growth between provenances was different at each site. Productivity per hectare was influenced by markedly different survival rates of provenances from the initial planting of 1040 seedlings ha^{-1}, and the most vigorous provenance at each site had an MAI approaching the maximum of 45.6 m^3 y^{-1} reported by Hingston *et al*. (1998) for the area with higher rainfall.

DBHOB of the harvested trees ranged from 217 to 367 mm, and height ranged from 21.8 to 31.1 m. Between the three provenances, there was little difference in the mean DBHOB, but there was a larger difference in the mean height (Table 2).

Table 1. Growth characteristics of trees within the measurement plot of each provenance at each site

Tree properties	Heath Block			Johnstons Block		
	Jeeralang	King Is.	SE Tas	Jeeralang	King Is.	SE Tas
Stocking (stems per hectare)	833	1042	917	958	875	458
Mean DBHOB (mm)	175	217	182	232	216	257
SD of DBHOB (mm)	86	50	81	52	70	67
Basal area (m2 per hectare)	24.6	40.6	28.3	42.3	35.2	25.2
MAI (m3 per year)	21	41	23	37	27	21

Table 2. Measured growth characteristics of the harvested trees

Tree properties	Heath Block			Johnstons Block		
	Jeeralang	King Is.	SE Tas	Jeeralang	King Is.	SE Tas
Mean DBHOB (mm)	279	265	265	290	282	287
Mean tree height (m)	25.1	30.0	24.6	26.6	22.8	24.9
Mean height at low crown (m)	12.0	17.6	13.4	12.0	11.8	13.4
Mean diameter at low crown (mm)	161	152	144	184	164	172
Mean volume of tree stem (m^3)	0.524	0.476	0.4	0.574	0.564	0.568

None of the trees in the two blocks had a 'perfect' shape. All trees had various amounts of localized sweep and elliptical stems. At only ten years of age, the trees had not over-grown stem 'imperfections'. A distinct difference in bark thickness was observed between the Jeeralang and the two other provenances. The bark of the Jeeralang provenance averaged 18 mm in thickness and was held tightly, making removal from the stems difficult. In contrast, the other two provenances had thinner (12 mm) and more stringy bark, which was easier to remove. Butt sweep was commonplace in almost all the trees at Heath Block as a result of the site having little protection from wind. Butt sweep was less obvious in the trees at Johnstons Block. Wandering pith of varying severity was frequently observed in a number of the sawlogs.

The frequency and the diameter of branches varied considerably and did not appear to be solely related to the proximity of the trees to the edge of the plantations. All harvested trees were more than 10 m from the edge of the plantation. However, no data were collected on tree branches due to limited time and resources. A number of trees appeared to have 'spiral bark', but such characteristic was found to be an unreliable indicator of spiral grain in the wood immediately adjacent. A similar finding

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[2] The Australian standard for hardwood appearance grade was under revision at the time. Our boards were therefore graded using an in-house grading criterion for hardwood appearance sawn timber.

was made earlier on Tasmania-grown *E. globulus* plantations (Yang and Waugh 1996).

Analysis of mean growth strain values for each tree

The analysis of tree means for growth strain is presented in Table 3. The error term for this analysis is the differences between individual trees and is suitable for testing for differences between sites and provenances. It also enables calculation of the number of trees required to discriminate between provenances (Downes *et al.* 1997) when measurements are carried out in this way (four heights and three positions per tree). There were significant differences between sites and highly significant differences between provenances (Table 3). The tree mean growth strain at Johnstons Block was higher in all three provenances than at Heath Block (Fig. 1).

Table 3. Analysis of tree mean values for growth strain

Source of variation	d.f.	Mean squares	Variance ratio
Site	1	592521	6.13*
Provenance	2	1202470	12.43***
Site x provenance	2	248794	2.57n.s.
Residual	53	96718	

*** significant at P=0.001; * significant at P=0.05; n.s. = not significant

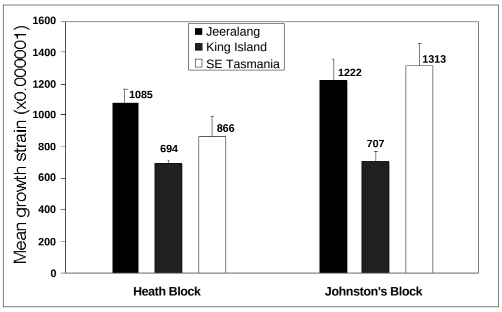

Figure 1. Mean growth strain of six tree groups averaged from measurements at four heights and three circumferential locations at each height. Error bars represent the standard error of differences between means.

Growth strain difference between provenances

Overall, there was no significant difference between Jeeralang and SE Tasmania provenances, but both provenances had significantly higher growth strain than King Island provenance (Fig. 1). Jeeralang provenance may have had higher growth strain, followed by SE Tasmania, then King Island provenances, if the stocking had been similar at both sites.

Interaction between sites and provenances

The mean growth strain of SE Tasmania provenance at Johnstons Block was not only 1.52 times as high as that at Heath Block, but also higher than those of Jeeralang provenance grown at both sites (Fig. 1). The higher mean growth strain of SE Tasmania provenance at Johnstons could be associated with markedly lower stocking than that at the Heath (Table 2), but was not sufficient to cause the interaction to be significant. Trees of SE Tasmania provenance at Johnstons Block showed greater incidence of pronounced spiral grain (e.g. close to 1:10 and above) than any other provenances. Also, they had a high incidence in frequency and quantity of kino. In fact, the large quantity of kino exuding from the bark gave a few trees a severely 'wounded' look. The extent of spiral grain and kino, however, were found not to have a definite relationship with mean growth strain of the trees.

Analysis of individual growth strain values

The analysis of individual growth strain measurements is presented in Table 4. The error term for this analysis was the variation caused by circumferential locations around the stem and so is not suitable for testing differences between provenances or sites. However, it is suitable for testing for differences between sampling heights and between trees.

Between-tree variation

The mean growth strain varied between trees within a single tree group. Figure 2 shows the mean growth strain of individual trees for each tree group. The data are presented in ascending order within each tree group for clarity. At each site, King Island provenance had the least between-tree variation. The highest between-tree variation was found in the SE Tasmanian provenance at Johnstons Block. The amount of between-tree variation of all six tree groups lies in a range approximately similar to those observed in young plantation-grown *E. nitens* (Chafe 1985) and regrowth *E. regnans* and *E. obliqua* (Nicholson 1973). The highly significant differences between individual trees (Table 4) indicate that genetic differences within provenances or environmental differences related to planting position are important in determining growth strain.

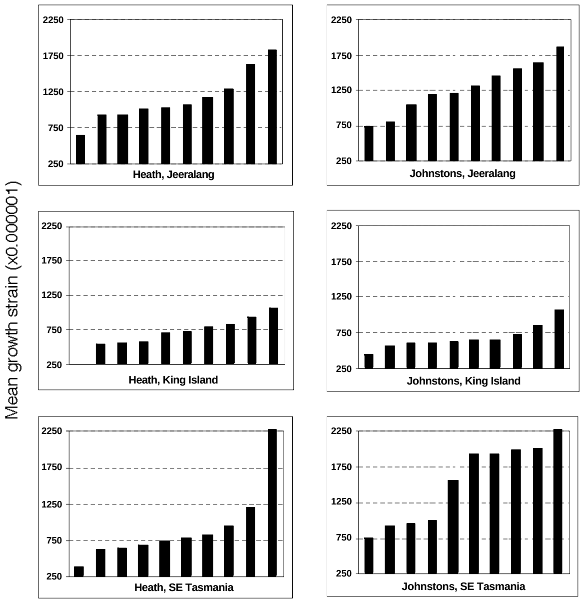

Figure 2. Mean growth strains of 59 individual trees averaged from measurements at four heights and three circumferential locations at each height for each tree. The data are presented in an ascending order within each tree group.

Variation with height

There were no significant differences in mean growth strain between heights (Table 4). On an individual tree basis, some trees had an increasing trend of growth strain with height, whereas some had a decreasing or no pattern of growth strain (Fig. 3). Quantitatively, on the other hand, the mean growth strain of each tree group reduced with height (Fig. 4). Only Jeeralang and King Island provenances at Johnstons Block did not entirely fit into this pattern. The mean growth strain of these two groups at the 6.1 m height was greater than at some lower heights. A few trees in these two groups had exceptionally high growth strain at 6.1 m height, which inflated the mean growth strain of the two groups at that height. High growth strain appeared to relate closely to tree growth characteristics, i.e. stem straightness, tree height, length of the crown, DBHOB and taper. The trees that had exceptionally high growth strain at 6.1 m height generally had the greatest lengths of crown, the highest ratio of tree height to DBHOB, and the smallest DBHOB. Or, these characteristics, together with taper, were greater than those for other trees in the two groups.

Chafe (1985) found a significant negative relationship between growth strain (and growth stress) and height of measurement in eight-year-old plantation *E. nitens* Maiden over a 15 m span.

Notice that the span in that study was much greater than in this study (6.1 m). In 39-year-old regrowth *E. regnans* F. Muell., however, the mean growth strain was found to increase with tree height over a 7.5 m span, although the relationship was not significant (Chafe 1981). Chafe (1985) suggested that these different results could be interpreted in terms of different stages in tree maturity. Our present results support this opinion.

One may argue that lower mean growth strain in bushlogs than that measured on the standing tree at 1.3 m was a result of stress release upon tree falling. It is true that a change in pattern and range of growth stress did occur when a tree was felled, but the mean values before and after felling, at approximately the same height (e.g. 1.5 m), changed only slightly, and hence are comparable (Nicholson 1973; Chafe 1985). Additional growth stress reduction in bushlogs probably had also occurred during the six-week log storage. However, such reduction should have occurred at all heights in the bushlogs. Therefore the original strain-height pattern in trees should have been reflected in the bushlogs after felling.

Table 4. Analysis of variance of individual measurements

Source of variation	d.f.	Mean squares	Variance ratio
Site	1	7.059E+06	-
Provenance	2	1.438E+07	-
Site x provenance	2	2.994E+06	-
Trees within provenance at each site	53	1.158E+06	3.86***
Sampling height within trees	177	3.080E+05	1.03n.s.
Residual	470	3.002E+05	

*** significant at P=0.001; n.s. = not significant

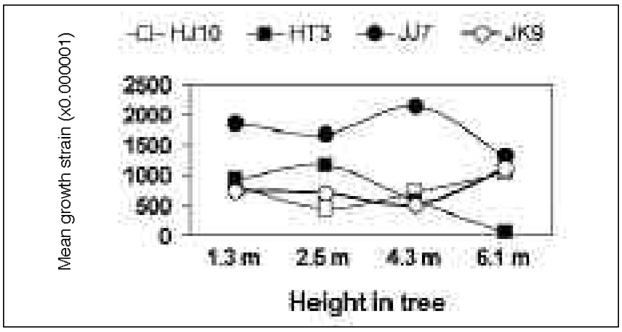

Figure 3. Mean growth strain with height for selected individual trees; the legend indicates the tree group and the tree number in that group.

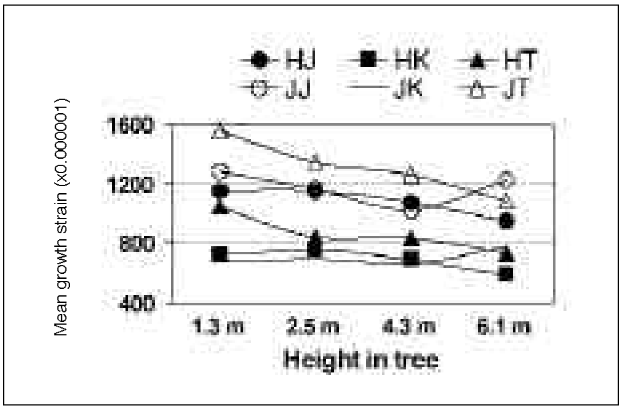

Figure 4. Mean growth strain of six tree groups at four heights. Values for each height are the means of three measurements made on all the trees in each individual group.

If mean growth strain does decrease with height in younger trees, it would have significant implications for growth strain sampling, especially if growth strains at a lower height (e.g. breast height) were closely correlated with those at other heights, as well as correlation with the mean growth strain over several heights (Table 5). Firstly, the measurement of strain at several heights in the forest is highly impractical. Secondly, if ground-level strain is used as a predictor of sawn board distortion, the amount of distortion is unlikely to be underestimated. Data in Table 5 suggest that the breast height measurements have a modest relationship with bushlog growth strain. Future work is needed to investigate the full-stem growth strain distribution with height in trees of various ages. When it is known how tree dimensions affect growth strain level, the within-tree distribution of growth strain (e.g. height distribution) might be manipulated through forest management.

Table 5. Correlation coefficients between mean growth strain at 1.3 m and each of those at other heights and the mean of bushlogs

Source of material	Mean at 2.5 m	Mean at 4.3 m	Mean at 6.1 m	Mean of three heights (2.5, 4.3 and 6.1 m)	Mean of four heights
HJ	0.16	0.33	0.28	0.31	0.63
HK	-0.25	-0.13	0.33	-0.13	0.61
HT	0.26	**0.69**	0.60	**0.72**	**0.93**
JJ	0.34	0.10	0.27	0.52	0.47
JK	0.19	0.55	0.46	0.57	0.56
JT	0.54	0.39	0.19	0.46	**0.71**
All 59 logs	**0.47**	**0.45**	**0.44**	**0.62**	**0.79**

Note: Correlation coefficients that are significant (P<0.05) are in bold

Analysis by sampling position and height up stem

Results of analyses by sampling position and height in the stem are presented in Table 6. At 1.3 m, position C results in the smallest residual mean square (and hence standard errors for means). But at 4.3 m, position A gives the smallest residual mean square. This height, however, is impractical for the measurement of growth strain. Position C at 1.3 m therefore would seem the practical choice.

Table 6. Residual mean squares from analyses by sampling position and height up stem

Sampling height up stem (m)	Sampling position		
	A	B	C
1.3	394 888	411 899	199 776
2.5	279 911	629 549	354 403
4.3	181 840	233 500	470 704
6.1	330 911	492 214	399 354

The sampling heights and positions gave generally the same rankings for the provenance means. The exception was position A at 1.3 m, where SE Tasmania ranked lower than Jeeralang, compared with positions B and C where Jeeralang was lower than SE Tasmania. In all cases King Island ranked lower than the other two provenances.

Residual mean squares may also be used to calculate the required sample size for the detection of significant differences between means. To detect mean differences of about 300 x 10^{-6} (the King Island mean was 340 x 10^{-6} less than that for SE Tasmania), and using position C at 1.3 m, a sample size of about 10 trees would be required (Steele and Torrie 1960, p. 86). A sample size of 19 would be required at sampling position A at 1.3 m, but at 4.3 m and position A, 9 trees would be sufficient. These results suggest that the methods used were adequate for detecting large provenance differences in growth strain. The sample size probably would not be sufficient for more subtle differences between families within provenances. Using the mean of all three sampling positions and all four heights reduced the residual mean square to 96 718 (Table 3). In this case, a sample size of 20 would permit discrimination of difference between means by about 145 x 10^{-6} at the 5% level of significance. Some of the residual variation is caused by individual differences between trees, and some is caused by the accuracy of Nicholson's method (repeatability is likely within 10% - Nicholson (1971)).

Relationships between tree dimensions and growth strain

Relationships between tree dimensions and mean growth strain at 1.3 m were examined. Unless otherwise specified, growth strain or mean growth strain in this section refers to that at 1.3 m.

The DBHOB and the ratio of tree height to DBHOB have more consistent relationships with mean growth strain than do other tree dimensions (Table 7). For these two tree parameters the relationships are negative and positive, respectively, for all the tree groups except for the SE Tasmanian provenance at Heath Block. In addition, the magnitude of the correlation coefficients varies least across those five tree groups. No apparent reason for differences in the SE Tasmanian provenance can be offered at this stage.

Table 7. Correlation coefficients between mean growth strain at 1.3 m and various tree measurements

Tree measurements	HJ	HK	HT	JJ	JK	JT	All logs
DBHOB	-0.41	-0.34	0.50	-0.36	-0.	-0.66	-0.05
Tree height	-0.22	0.52	0.04	0.19	0.	-0.52	-0.10
Height of low crown	0.26	0.53	-0.43	-0.10	0.	-0.23	-0.20
Diameter at low crown	**-0.68**	-0.01	**0.70**	-0.45	0.	-0.20	0.15
Taper	0.04	-0.40	0.22	**0.74**	-0	-0.47	0.23
Ratio of tree height to DBHOB	0.25	0.45	-0.41	0.44	0.54	0.42	-0.05
Vertical length of crown	-0.47	-0.26	0.31	0.23	0.06	-006	0.12

Notes:

1. The ratio of tree height to DBHOB is calculated as tree height divided by 0.5*DBHOB to the power of 3
2. Correlation coefficients that are significant (*P*<0.05) are in bold

The negative relationship between tree DBHOB and growth strain makes sense in terms of tree stability and survival. Tree height and size of the crown are critical in considering bending moment. Under the same bending moment, and with everything else being equal, the larger the tree diameter the lower are the bending stresses generated at the tree surface and the less the tree bends. In reality, larger trees are usually taller, have larger crowns and therefore are more likely to be subject to a greater bending moment. Still, the magnitude of bending stresses is influenced to a much greater extent by tree diameter than by bending moment (Gieck 1985, p.10). However, there seems to be no clear-cut relationship between growth strain and tree diameter. Positive relationships were found between growth strain and DBHOB for eight-year-old plantation *E. nitens* and 36-year-old regrowth *E. regnans* (Chafe 1995). Nicholson (1973) reported that growth stress was independent of DBHOB in 31-year-old regrowth *E. regnans*, but did not report whether there was a relationship for growth strain. Since the apparent function of growth stress is to stabilize or reorient tree stems (Kubler 1987), the actual relationship between growth stress or growth strain and tree diameter may vary in individual circumstances.

As far as other tree dimensions are concerned, the ratio of tree height to DBHOB increases when tree height increases and/or tree DBHOB decreases. This ratio could be a better indicator of growth strain at 1.3 m than either DBHOB or tree height alone. The relationships of mean growth strain with other tree dimensions have correlation coefficients that vary greatly across the tree groups (Table 7). The width and fullness of the crown are suspected to account for a degree of variation in mean growth strain, but were not measured. The wood density of the study trees is not available at this stage and its effect on growth strain remains to be quantified.

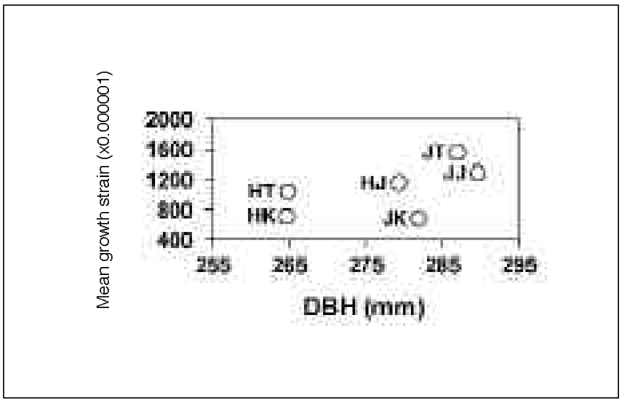

Figure 5. Relation of tree-group mean DBH to tree-group mean growth strain at 1.3 m for the three provenances from both sites

When comparing the mean DBHOB and growth strain on a provenance basis (Fig. 5), there seems to be a pattern of increase for both Jeeralang and SE Tasmania as the mean DBHOB increases. This also seems to indicate that the growth rates and growth strains of King Island provenance were less influenced by site characteristics than were those of the other two provenances.

Comparison to regrowth eucalypts

The Australian hardwood sawmilling industry has accumulated considerable experience in processing regrowth eucalypts since the resource base shifted from the old growth to regrowth. As plantation eucalypts will become a significant component of the future sawlog resource, properties of plantation *E. globulus* with reference to major commercial eucalypt species (regrowth or plantations), will be valuable to the industry. The data in Table 8 are limited to those determined using Nicholson's method (1971).

It is interesting to see that the likely range of mean growth strain of *E. regnans* and *E. obliqua* is 600 x 10^{-6} to 800 x 10^{-6}. Although only one study was done on *E. nitens*, mean growth strain of this species is not expected to vary greatly from this range primarily because *E. nitens* is known to have low growth stress.

In comparison to regrowth *E. regnans* and *E. obliqua* and plantation *E. nitens*, the King Island provenance of *E. globulus* lies in a similar growth strain range, whereas Jeeralang and SE Tasmania provenances are at least 30% greater in their mean growth strain (Table 8). Again, this demonstrates major differences in growth strain between species and provenances.

According to Kubler's (1959) longitudinal growth strain distribution model, with growth strain at log periphery being the same, the smaller a log is, the higher will be the growth strain gradient across the log stem. Boards sawn from a small log will display greater distortion (either bow or spring or both) than boards of the same thickness sawn from a large log. Compared with trees from regrowth forest, plantation trees are commonly harvested at a much younger age and, despite their faster growth rate, the logs are usually smaller in diameter. The presence of both higher growth strain and smaller diameter will only aggravate sawlog degrade and sawn board distortion.

Table 8. Comparison of mean growth strain (x10-6) in *E. globulus* at 1.3 m with some major commercial eucalypt species in Australia (regrowth or plantations)

Source of data	Lowest–strain trees		Highest-strain trees		Mean
	Single	Mean	Single	Mean	
E. globulus (1.3 m, this study)					
HJ	-40	651	2530	1834	1156
HK	80	458	1694	1069	748
HJ	299	412	5181	3546	1048
JJ	99	737	2854	1862	1284
JK	418	453	1392	1081	684
JT	-160	764	3115	2542	1561
*E. regnans*1 (31 yr regrowth) Nicholson (1973)	135	355	3245	1185	760
E. regnans (32 yr regrowth) Nicholson *et al.* (1975)	-	460	-	770	600
E. regnans (39 yr regrowth)2 Chafe (1981)	-	400	-	780	540
E. regnans (36 yr regrowth) Chafe (1990)	-	40	-	2450	770
*E. obliqua*3 (70 yr regrowth) Nicholson (1973)	253	466	1570	1127	737
E. obliqua (75 yr regrowth) Nicholson & Ditchburne (1973)	-	530	-	1600	730
E. nitens (8 yr plantation)4 Chafe (1985)	-	340	-	980	690

Notes:
1 These strain values were calculated from the original growth stress values in Nicholson (1973) using an average MOE value of 2x106 lbs in^{-2} (14080 MPa)
2 Mean strain at 2.5 m height
3 These strain values were calculated from the original growth stress values in Nicholson (1973) using an average MOE values of 15558 MPa which was derived from Nicholson and Ditchburne (1973)
4 Mean strain at 1.5 m height

Conclusions

(1) Mean growth strain throughout the stem was higher for all three provenances at Johnstons Block.

(2) King Island provenance had significantly lower growth strain than the Jeeralang and SE Tasmania provenances.

(3) Overall, King Island provenance had the lowest between-tree variation in mean growth strain as well as the lowest within-tree circumferential variation.

(4) There was no significant difference in mean growth strain between tree heights. Nevertheless, the data suggest that mean growth strain decreases with tree height in most trees.

(5) A single measurement per tree at breast height using sample sizes of between ten and twenty trees per provenance may be sufficient to detect large provenance differences. However, much larger sample sizes are likely to be required for detecting family differences.

(6) In comparison to regrowth *E. regnans* and *E. obliqua*, and plantation *E. nitens,* King Island provenance of *E. globulus*

lies in a similar growth strain range; however, Jeeralang and SE Tasmania provenances are at least 30% greater in their mean growth strain.

Note that the above conclusions were drawn from a sample of limited size and sampling options.

Acknowledgements

We wish to acknowledge the provision of the trees, assistance with harvesting and cartage of the logs to Creswick (Vic.), and assistance in supplying establishment information on the trials by Forestry SA. The logs were sawn at the Victorian Timber Industry Training Centre at Creswick. Mr D Gritton of CSIRO, Mr P Blackwell and Mr D Blackwell assisted with growth strain measurement. The Natural Heritage Trust (Australia) provided funds to support this research. Constructive comments from Ms C. Raymond, Dr G. Downes and Dr H. Wu are greatly appreciated.

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