2005

Growth stress in Eucalyptus dunnii

Timothy N. Murphy
Southern Cross University

Michael Henson
Forests NSW

Jerome K. Vanclay
Southern Cross University

Publication details

Murphy, TN, Henson, M & Vanclay, JK 2005, 'Growth stress in *Eucalyptus dunnii*', *Australian Forestry*, vol. 68, no. 2, pp. 144-149.
The abstract and pdf of the published article reproduced in ePublications@SCU with the permission of Australian Forestry.

Growth stress in *Eucalyptus dunnii*

Timothy N. Murphy[1,3], Michael Henson[2] and Jerome K. Vanclay[1,4]

[1]Sustainable Forestry Program, Southern Cross University, PO Box 157, Lismore, NSW 2480, Australia
[2]Forests NSW, PO Box J19, Coffs Harbour Jetty, NSW 2450, Australia
[3]Australian Forest Corporation, 75 Elliott Road, Lismore, NSW 2480, Australia
[4]Corresponding author, email: jvanclay@scu.edu.au

Revised manuscript received 28 April 2005

Summary

Growth stress in 9-y-old plantation-grown *Eucalyptus dunnii* was assessed by measuring longitudinal growth strain. Strain varied considerably (370–1560 μm^{-1}) and was sufficiently heritable (h^2 = 0.3–0.5) that tree breeding may be an effective way to reduce the incidence of growth stress in this species. Although the formation of longitudinal growth strain appears to be under strong genetic control (P = 0.0015), there was a tendency for tall thin trees to exhibit higher stress than short thick trees (P = 0.025 for height:diameter ratio). Two provenances and three families identified in this study show potential as superior material for further tree breeding.

Keywords: wood properties; growth stress; strain; heritability; *Eucalyptus dunnii*

Introduction

Eucalyptus dunnii Maiden (Dunn's white gum, Benson and Hager 1993) is a relatively new but increasingly important plantation species in eastern Australia. Over 10 000 ha of *E. dunnii* plantations have been established in New South Wales (NSW), and it remains one of the favoured species for planting, with some 40% of current plantings in north-eastern NSW and south-eastern Queensland using this species. Although it forms a crucial component of the long-term supply to the sawlog industry, this emerging plantation resource remains untried by industry.

The Regional Forest Agreements in 2000 (Davey *et al.* 2002), and the transfer of further State Forests to National Parks in NSW in 2003, have increased the need for plantations to supply sawlogs to the forest industries. As a result of these decisions, and because of increasing demand, there is a shortage of high-quality sawlogs within NSW. The response by government has been to establish, and to encourage private investment in, hardwood plantations (e.g. the *Plantations 2020 Vision*, which aims to increase plantation area by 2 million ha by 2020).

Eucalyptus dunnii, like most eucalypt species, suffers from growth stress that causes problems and financial losses in processing sawnwood. Fortunately, there is a great deal of natural variation in eucalypts in the propensity for growth stress (Swain *et al.* 2000; Yang *et al.* 2001), and the trait is heritable (Schacht *et al.* 1998), so there is scope to address this issue through tree breeding. The present study seeks to establish the extent of growth stress in a progeny trial of *E. dunnii*, to foreshadow the nature of the future mature timber resource and to provide guidance for further tree breeding efforts. While growth stress in 9-y-old trees is likely to be greater than that observed in mature sawlogs, the ranking of families with regard to this trait is likely to remain unchanged. Thus identifying families with high longitudinal growth strain at age 9 y, and removing these families from seed orchards and ongoing tree-breeding programs, will contribute to a better sawlog resource in the future.

Literature

Growth stress is a major cause of degrade and processing problems in eucalypts (e.g. Jacobs 1945; Grzeskowiak 2001). Foresters and sawyers have long been aware of these problems, and have devised a range of techniques to gauge stress and its impact on wood processing (e.g. Jacobs 1945; Boyd 1950; Nicholson 1971; Yang and Hunter 2000; Yang *et al.* 2005). Most of these methods involve cutting the xylem under controlled conditions and recording the longitudinal strain that is induced as the stress is relieved.

There is a great deal of natural variation in eucalypts in the propensity for growth stress (Swain *et al.* 2000; Yang *et al.* 2001, working with *E. globulus*), and the trait is heritable. For example, Schacht (1988) found that the heritability of growth stress in *E. urophylla* was 0.8, offering considerable scope to reduce this problem by conventional tree breeding. Few accounts of sawing studies of plantation-grown *E. dunnii* have been published, but results to hand suggest that as much as one-third of sawn material may suffer degrade attributable to growth stress (Matos *et al.* 2003).

Inferences may also be drawn from comparable studies with other eucalypt species. A study of 10-y-old plantation-grown *E. globulus* (Yang *et al.* 2002) revealed that 30% of sawn boards were rejected due to excessive distortion, and that 40% of this distortion could be attributed to growth stress. Distortion varied greatly throughout the study material (Yang *et al.* 2001), and could not be attributed to site or provenance (P >0.1; Yang *et al.* 2002).

The now-standard method of measuring growth strain near the cambium of standing trees by releasing stress was pioneered by Nicholson (1971; Archer 1986), and has been refined into three variants using ‘CIRAD’, resistance and transducer strain gauges. Bailleres and Yang (2003) compared the Nicholson, CIRAD and resistance strain gauges in eucalypts, and reported advantages and disadvantages of all three methods.

The CIRAD or French method (Bailleres *et al.*1995, 1997; Raymond *et al.* 2002; Loup 2003) couples a Mitutoyo dial gauge with a jig devised by CIRAD, and enables strain to be assessed relatively easily. Advantages of this method are that only one hole is required to release stress, and that CIRAD provides a standardised ‘ready-for-use’ jig that helps to make measurements comparable between different agencies. It has become something of a standard in Australia (Raymond *et al.* 2002), but CIRAD scientists now appear to favour the transducer approach (Beismann *et al.* 2000; Fournier *et al.* 1994; Plomion *et al.* 2000). The ‘single-hole’ approach employed by the CIRAD method records an absolute value about twice that recorded by the other methods (Yoshida and Okuyama 2002).

Resistance gauges are generally thin-film, general-purpose 120 ohm strain gauges measuring about 1 mm × 0.5 mm (such as Kyowa KDG-120-C1-11 gauges; Kikata 1972; Yoshida *et al.* 2000, 2002; Huang *et al.* 2002; Yoshida and Okuyama 2002). These gauges are glued to the xylem, and measured using a strain meter (e.g. Kyowa UCAM-1A) relying on a Wheatstone bridge. Strain is measured by making small cuts above and below the gauge to release the growth stress. Yoshida and Okuyama (2002) recommended that these cuts should be standardised at about 5–10 mm deep and 3–10 mm from the gauge. The length of the cut should be about 1.5 times the distance from the gauge (Saurat and Gueneau 1976).

Transducer gauges are a less intrusive analogue of the resistance gauges. The advantage of the transducer approach is that the gauge is attached to the tree with two probes, and need not be glued. Recent work with transducers (Fournier *et al.* 1994; Beismann *et al.* 2000; Plomion *et al.* 2000) has used a DD1 strain transducer manufactured by Hottinger Baldwin Messtechnik, a small (64 mm × 26 mm × 10 mm), light (20 g) and portable instrument (Yang *et al.* 2005 illustrate this instrument in their Fig. 3).

Growth strain may vary considerably within a tree, and more than one measurement is needed to reliably quantify strain. Raymond *et al.* (2002) examined a range of methods for assessing growth stress, by using strain gauges (up to 36 measurements taken at four aspects and nine heights), measuring board deflection, and by assessing end splitting. They concluded that two measurements of strain taken at or near breast height could provide an adequate and efficient estimate of growth stress that correlated well with other methods.

Study site

The study was conducted in a 9-y-old progeny trial (Johnson and Arnold 1998) at Boambee State Forest (30°18′S, 153°03′E, 60 m asl), south-west of Coffs Harbour, during January and February 2004. Boambee experiences a mild temperate climate (average daily temperature 14–23°C), with a median rainfall of 1585 mm. The soils are yellow podsolics over shale geology.

Eucalyptus dunnii has a limited distribution in and near the Border Ranges of NSW and Queensland (Boland *et al.* 1984; Benson and Hager 1993; Specht *et al.* 1995). The Boambee progeny trial contains seedlings raised from 219 open-pollinated (family) seedlots collected from individual *E. dunnii* trees in wild populations throughout most of this range. These seedlots were collected by the CSIRO Australian Tree Seed Centre between 1986 and 1991, and represent 21 different provenances, numbered 1–21 from north to south. Each seedlot was represented in the trial by six replicates of four-tree row plots arranged as incomplete block designs with one-dimensional blocking within replicates. Trees were spaced at 3.0 m (between rows) × 2.4 m (within rows).

The study site was previously an *E. grandis* plantation, which was clearfelled at age 40 y. Logging debris was pushed into windrows and burnt in the spring of 1994. A winged ripper pulled by a crawler tractor ripped planting lines to a 50–60 cm depth between the stumps. Regrowth of woody weeds was sprayed with glyphosate herbicide in December 1994. The trials were hand-planted in February 1995 with sun-hardened seedlings in Hiko V93 cells. Within a month of planting, each seedling received one 20 g Langley Tree Tablet (N 20%: P 4.4%: K 8.2%: S 6.0%), buried 10 cm deep about 15 cm away from the seedling. Thinning at age 4 y removed the poorest two trees from each four-tree row plot, based on a subjective estimate of tree volume and stem form (Johnson and Arnold 1998). At the time of last measure in late 2003, trees averaged 23 cm diameter (breast height, over bark) and 28 m in height.

Method

Fifty-two families from 15 provenances were selected for strain measurement on the basis of their superior growth. Strain in all the standing trees of these families and provenances (164 trees in all) was measured with resistance strain gauges in accordance with the procedures outlined by Yoshida and Okuyama (2002). Strain in some of the trees was also measured with the DD1 transducer (in addition to the standard resistance gauge measurement). The DD1 was not available in Australia at the time this study commenced, and was used on only the final 18 trees assessed in this study. Because of this small sample and haphazard selection, strain estimates from the DD1 were not used to rank families. The DD1 results are reported only because the instrument has not previously been compared with more established methods (Yang *et al.* 2005).

Resistance strain gauges require a window to be cut into the bark so that the gauge can be glued to the cambium and initialised. Once that is done, growth stress is released by making small cuts above and below the gauge, and the strain is recorded on the gauge. The time-consuming part of this procedure is cutting the window in the bark, gluing the gauge in place, and allowing the glue to cure. The precision part — initialising the gauge, cutting the slot and recording strain — must be done carefully, in calm conditions. Thus it is prudent to cut the windows and place the gauges in advance (e.g. the afternoon before), and to read them the following day (e.g. at dawn, and for as long as calm conditions prevail).

The placement of the window and the cut is critical to accurate measurement of strain. Two measurements per tree are needed to get reliable data (Raymond *et al.* 2002). Notwithstanding the Muneri *et al.* (1999) finding that orientation does not matter, we standardised measurements by aligning them in the plane of any

Figure 1. *Eucalyptus dunnii* tree during strain measurement. The flagging tape indicates that the tree has been prepared ready for measurement.

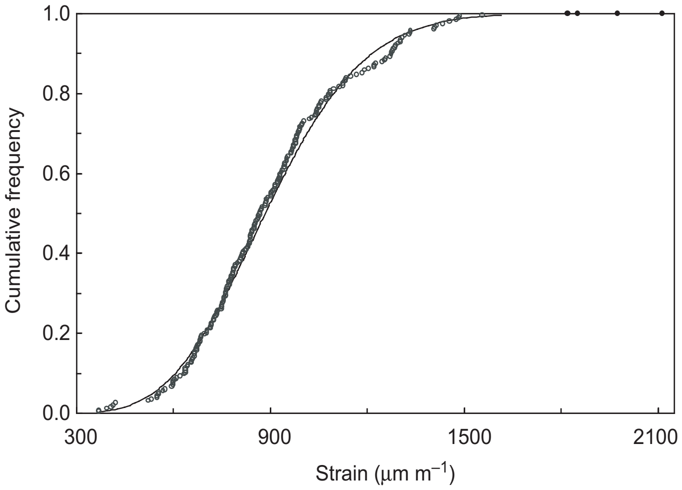

Figure 2. Strain data compared with the square of the cumulative normal distribution (N~$(29.7,4.0)^2$). The four outliers are evident at top right, and are shown as solid circles. Mean strain is 883 $\mu\mathrm{m}^{-1}$, and about 10% of trees have strain less than 600 $\mu\mathrm{m}^{-1}$.

tree lean (i.e. on the 'up' and 'down' side of any lean) or crown asymmetry where present, to record the minimum and maximum strain present in each tree. A portion of the bark at breast height was carefully removed to expose, but not affect, the cambium. The cambial surface was scraped to remove the differentiating xylem and then cleaned with ethyl alcohol (Yoshida and Okuyama 2002). The strain gauge was glued on the cleaned surface using cyanoacryalate-based glue, and the bond was allowed to cure.

When the tree was re-visited to record the strain, a wire was soldered to the strain gauge using a flameless cigarette lighter, to connect the gauge to the meter in a half-bridge configuration with a 'dummy' gauge (of the same resistance, make and batch). For the 18 trees measured using both resistance and transducer gauges, the DD1 was attached to the tree, astride and concentric with the pre-glued resistance gauge. The strain meter was initialised (zeroed) and allowed to stabilise. When the fluctuation in the strain value was less than 20 mm^{-1} (micrometres per metre, or parts per million), the stress relaxation was initiated by making slots 10 mm above and below the strain gauge. These slots were standardised at 20 mm deep and 20 mm wide with a battery-operated hand drill (with a 6 mm drill-bit and a sleeve to ensure a consistent depth; Fig. 1, visible as two horizontal lines of drill shavings, above and below the gauge).

Results

Preliminary analysis of the data revealed four outliers (trees 162, 584, 2808 and 3272). A Box–Cox procedure (Box and Cox 1964, 1982) indicated that a square-root transformation was appropriate to normalise these data. After this transformation, the data were close to normal (Fig. 2), with mean 883 $\mu\mathrm{m}^{-1}$ and standard deviation about ±240 $\mu\mathrm{m}^{-1}$, after back-transforming. The four outliers are clearly evident in Figure 2, and represent trees with severe lean (tree 584), or instances where wind gusts were experienced during stress release (trees 162, 2808 and 3272). These outliers were omitted from further analysis.

Subsequent analyses revealed that all 15 provenances exhibited wide variation in strain, with some individuals in most provenances exhibiting high levels of strain (Fig. 3). Two exceptions were provenances 10 and 13, both of which exhibited many individuals with low strain, and small mean values. Provenances 6 and 10 both include an individual with unusually high strain, but as there was no reasonable basis to exclude these data, they were included in all analyses.

The present study involved 52 families, so an illustration comparable to Figure 3 at the family level is too crowded to interpret. Figure 4 offers a summary of seven families of interest, representing the best and the worst of the families. This simple summary illustrates the great variation between families and indicates that strain is not merely a product of stem size or growth rate.

An analysis of variance (Table 1) confirms these effects. Replication (five plots) is not significant, and the main effect is genetic (family). The combined effect of provenance and family is highly significant ($F_{51,163} = 1.88$, $P = 0.0015$). The height: diameter ratio of trees is also significant ($P = 0.031$):

$$Strain = (Family_i + 4.96Ht/Dbh)^2\,, \qquad (1)$$

where *Strain* is measured growth strain ($\mu\mathrm{m}^{-1}$), $Family_i$ is the family mean (e.g. 25.24 for Family 1), *Ht*/*Dbh* is tree height (m) divided by diameter at breast height over bark (cm, s.e. = 1.80).

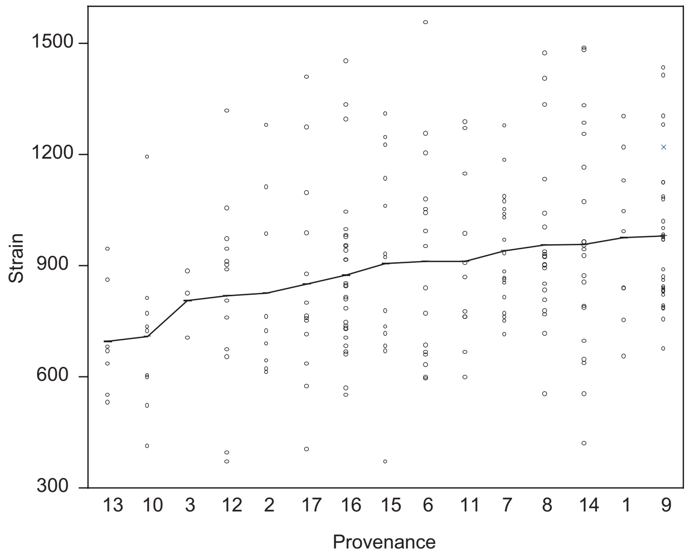

Figure 3. Strain measurements within each of 15 provenances, showing strain in individual trees (o) and for provenance-wide averages (–). Provenances 10 and 13 are noteworthy, having generally low values of strain, as well as small mean values. Provenances are numbered systematically from north to south.

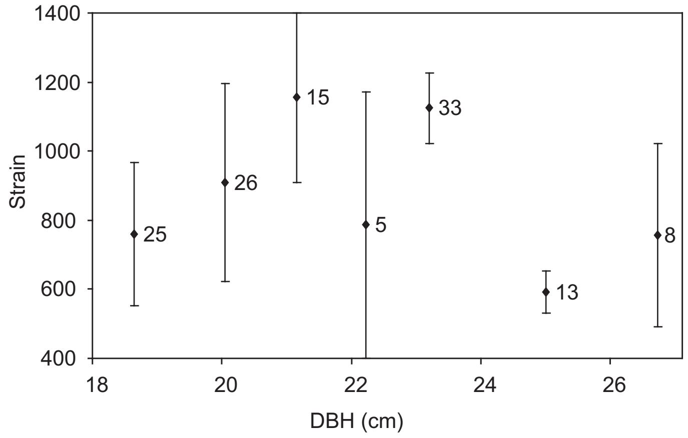

Figure 4. Strain measurements within selected families illustrating the best and worst performance amongst families sampled by two or more individuals. Vertical lines indicate the mean strain plus and minus one standard error. The figure illustrates Families 25 (smallest mean dbh), 26 (shortest mean height), 15 (largest mean strain), 5 (highest variance), 33 (highest minimum, i.e. all samples ≥ 1038 $\mathrm{mm^{-1}}$), 13 (tallest mean height, and lowest mean strain), and 8 (largest mean dbh).

Table 1. Analysis of variance (ANOVA) for strain showing the influence of family

Source	df	MS	*F*	*P*	
Replication	4	23.97	1.85	0.121	ns
Provenance	14	27.16	2.10	0.014	*
Family (within provenance)	37	23.26	1.80	0.007	**
Tree height:dbh ratio	1	61.57	4.76	0.031	*
Residual	163	12.92			

This suggests that tall thin trees are likely to exhibit more strain than short thick trees. This equation was used to prepare Figure 5, which illustrates the expected strain in a tree with an average height:diameter ratio (1.24 $\mathrm{m\ cm^{-1}}$) within each family.

Several other environmental factors were also examined, but were found to be non-significant. Time of day, temperature, humidity, wind speed (note that measurements were not taken if strain fluctuation exceeded 20 $\mu\mathrm{m}^{-1}$) and date of measurement were all non-significant ($P > 0.4$).

Table 1 illustrates that both provenance, and family within provenance, have a significant influence on the expression of longitudinal growth strain. A more formal analysis using restricted maximum likelihood estimation (ASREML, Gilmour *et al.* 1999) indicates a heritability of 0.52 (s.e. = 0.27, $P = 0.027$), using the conventional assumption that open-pollinated trees have a relatedness coefficient of 4. With the more conservative assumption of a relatedness coefficient of 2.5 (to account for the fact that open-pollinated progenies may comprise a mixture of self and outcrosses, Griffin and Cotterill 1988), the heritability is estimated as 0.32 (s.e. = 0.17, $P = 0.027$). In either case, the heritability is significant, and offers the prospect of worthwhile gains through conventional tree breeding.

The DD1 transducer gave readings consistent with those from the resistance gauges. Initial attempts to use with both strain gauges in a concentric configuration were not always successful, and the DD1 was sometimes bumped or dislodged. As a result, 29 paired strain observations were available from 15 of the 18 trees measured with both approaches. Regression analyses revealed a close linear correlation ($r^2 = 0.89$, $P < 0.001$), with no evidence of curvature ($P > 0.8$) or heterogeneous variance ($P > 0.9$). The raw DD1 readings indicated strain estimates 23% higher than the resistance gauges ($t = 7.6$, $P < 0.001$), because the DD1 had not been calibrated after fitting the pins for use on trees. Subsequent laboratory tests confirmed the close correlation between the DD1 and resistance gauges ($r^2 \geq 0.99$). The highest correlations were obtained when the DD1 pins penetrated 1 mm into the xylem ($r^2 \geq 0.999$); when the pins were pressed 2 mm into the wood, the correlation decreased slightly (to $r^2 = 0.99$) and a discrepancy was observed (the DD1 was consistently 30% lower). The utility of the DD1 is undergoing further evaluation, but field staff consider that the DD1 is quicker and more convenient to use than the glue-on resistance gauges.

Discussion

Individual trees in the 9-y-old *Eucalyptus dunnii* plantation under investigation exhibited growth strain in the range 360–1560 $\mu\mathrm{m}^{-1}$. Growth stress is of little consequence for pulpwood, but is of concern in solid wood products. Most (90%) of the trees studied exhibited growth stresses above 650 $\mu\mathrm{m}^{-1}$, the level at which processing losses become apparent (Prof. J. Walker, University of Canterbury, *pers. comm.*, 2003), so the issue is topical and warrants research and management. Four avenues for managing growth stress may be considered: longer rotations, silviculture, tree breeding, and new processing techniques. Longer rotations may alleviate growth stress, but may be neither economically nor politically feasible in NSW. No published studies have demonstrated a reduction in growth stress through silviculture,

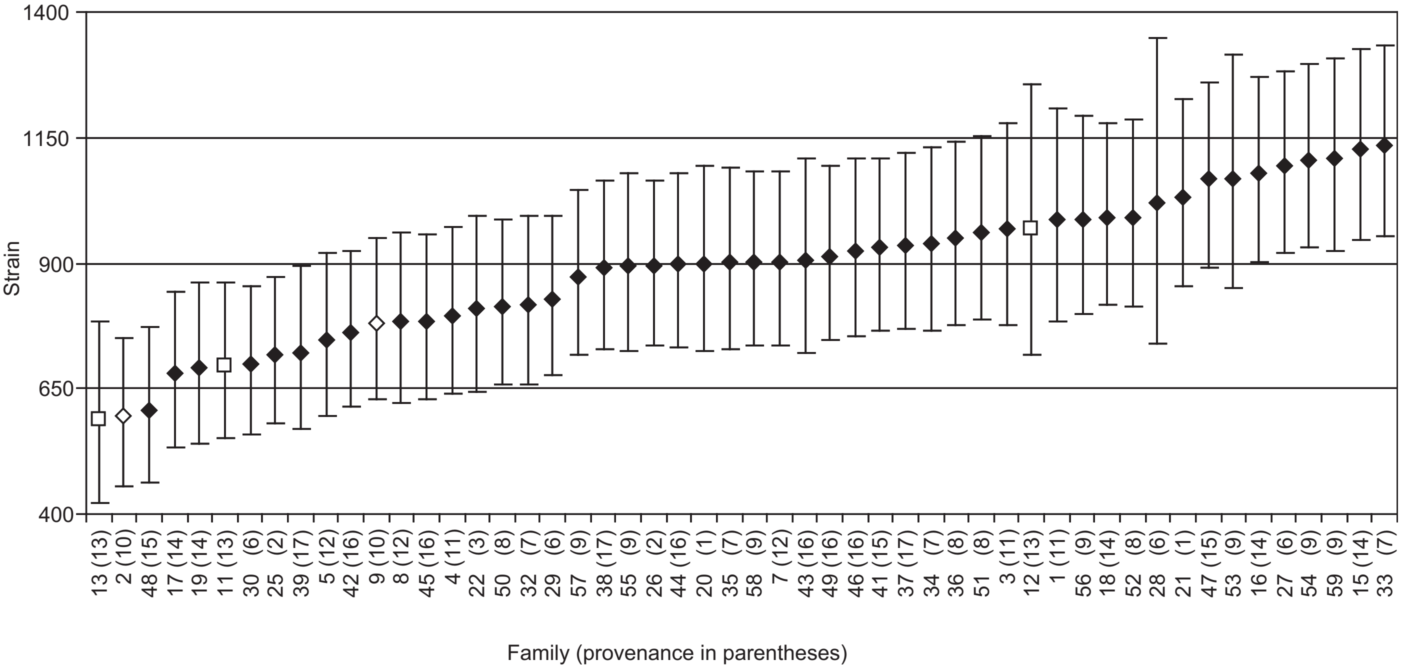

Figure 5. Expected mean family strain, adjusted for mean tree diameter and height. Vertical bars indicate plus and minus one standard error. Families 13, 2 and 48, and provenances 13 and 10 exhibit the lowest strain: □ = provenance 13; ◇ = provenance 10.

but this aspect may warrant attention, given the extent and nature of the resource in the region. In the short term, new technology such as the Hewsaw (Kaliteevskii 2003) offers some promise to alleviate problems with growth stress, but in the longer term the best option appears to be tree breeding to reduce growth stress in future plantings. Our data imply a heritability of 0.3–0.5, which suggests that conventional tree breeding could offer a substantial change in the propensity of trees to develop growth stress. This warrants urgent attention.

Conclusion

Nine-year-old plantation-grown *Eucalyptus dunnii* exhibit longitudinal growth strain in the range 360–1560 μm^{-1}, with 90% of trees exhibiting stress sufficiently high to be of concern to sawmillers. As the tendency to form high growth stress is heritable (h^2 = 0.3–0.5), there is scope to reduce growth stress through conventional tree breeding. We identified three families with particularly low growth stresses.

Acknowledgements

This work funded by State Forests of NSW and Southern Cross University through Collaborative Research Grant 50415-30535. The DD1 transducer was supplied by Rinstrum PL, Acacia Ridge, and adapted for use on trees by AWE Engineering, Lismore. We thank Drs John Walker and Shakti Chauhan (University of Canterbury) for advice and loan of equipment, Yin Yafang (Chinese Academy of Forestry) for assistance, Jim O'Hara and Steve Boyton (State Forests of NSW) for field support, Prof. Peter Baverstock and Steve Williams (Southern Cross University) for logistical support, and Miriam Murphy for field assistance.

References

Archer, S.T. (1986) *Growth Stresses and Strains in Trees*. Springer, Berlin.

Bailleres, H. and Yang, J. (2003) Improved wood quality of eucalypt plantations for high value products. Sir Frederick McMaster Fellowship Report, CSIRO Forestry and Forest Products, Client Report No. 1271, 25 pp.

Bailleres, H., Chanson, B., Fournier, M., Tollier, M.T. and Monties, B. (1995) Structure, composition chimique et retraits de maturation du bois chez les clones d'*Eucalyptus*. *Annales des Sciences Forestières* **52,** 157–172.

Bailleres, H., Castan, M., Monties, B., Pollet, B. and Lapierre, C. (1997) Lignin structure in *Buxus sempervirens* reaction wood. *Phytochemistry* **44,** 35–39.

Beismann, H., Wilhelmi, H., Bailleres, H., Spatz, H-C., Bogenrieder, A. and Speck, T. (2000) Brittleness of twig bases in the genus *Salix*: fracture mechanics and ecological relevance. *Journal of Experimental Botany* **51,** 617–633.

Benson, J.S. and Hager, T.C. (1993) The distribution, abundance and habitat of *Eucalyptus dunnii* (Myrtaceae) (Dunn's white gum) in New South Wales. *Cunninghamia* **3,** 123–145.

Boland, D.J., Brooker, M.I.H., Chippendale, G.M., Hall, N., Hyland, B.P.M., Johnston, R.D., Kleinig, D.A. and Turner, J.D. (1984) *Forest Trees of Australia*. 4th edition. Nelson and CSIRO, Melbourne.

Box, G.E.P. and Cox, D.R. (1964) An analysis of transformations. *Journal of the Royal Statistical Society* **B 26,** 211–252.

Box, G.E.P. and Cox, D.R. (1982) An analysis of transformations revisited. *Journal of the American Statistical Association* **77,** 209–210.

Boyd, J.D. (1950) Tree growth stresses. I Growth stress evaluation. *Australian Journal of Scientific Research* B (Biological Sciences) **3,** 270–293.

Davey, S.M., Hoare, J.R.L. and Rumba, K.E. (2002) Science and its role in Australian regional forest agreements. *International Forestry Review* **4,** 39–55.

Fournier, M., Chanson, B., Thibaut, B. and Guitard, D. (1994) Mesure des déformations residuelles de croissance a la surface des arbres, en relation avec leur morphologie. Observations sur différentes espèces. *Annales des Sciences Forestières* **51,** 249–266.

Gilmour, A.R., Cullis, B.R., Welham, S.J. and Thompson R. (1999) *ASREML Reference Manual*. SW Agriculture Biometric Bulletin No. 3. NSW Agriculture, Orange.

Griffin, A.R. and Cotterill, P.P. (1988) Genetic variation in growth of outcrossed, selfed and open-pollinated progenies of *Eucalyptus regnans* and some implications for breeding strategy. *Silvae Genetica* **37,** 124–131.

Grzeskowiak V., Turner, P. and Sefara, N.L. (2001) Potential of screening tools for early prediction of splitting and brittleheart in *Eucalyptus grandis*. CSIR internal report ENV-D-C-2001-91. Cited in Turner, P. (2001) Strategic and tactical options for managing the quality and value of eucalypt plantation resources. *Developing the Eucalypt of the Future.* IUFRO Conference, Valdivia, Chile.

Huang, Y.S., Chen, S.S., Lin, T.P. and Chen, Y.S. (2002) Growth strain in coconut palm trees. *Tree Physiology* **22,** 261–266.

Jacobs, M.R. (1945) *The Growth of Woody Stems*. Commonwealth Forestry Bureau, Australia, Bulletin No. 28, 67 pp.

Johnson, I.G. and Arnold, R.J. (1998) Eucalyptus dunnii *Provenance-Family Trials in Northern New South Wales — Age Three-Year Assessment*. State Forests of NSW Research Paper 37, 28 pp.

Kaliteevskii, R.E. (2003) Classification of log sawing machinery and development trends. (Russian). *Derevoobrabatyvayushchaya Promyshlennost* **2003**(1)**,** 9–11.

Kikata, Y. (1972) The effect of lean on level of growth stress in *Pinus densiflora*. *Mokuzai Gokkaishi* **18,** 443–449.

Loup, C. (2003) How to measure stresses in trees. Laboratoire de mécanique et de Génie civil, Université de Montpellier, France. 9 pp.

Matos, J.L.M., Iwakiri, S., Rocha, M.P., Paim, R.M. and Andrade, L.O. (2003) Redução do efeito das tensões de crescimento em toras de *Eucalyptus dunnii* (Reduction of growth stress effects in the logs of *Eucalyptus dunnii*). *Scientia Forestalis* **64,** 128–135.

Muneri, A., Leggate, W. and Palmer, G. (1999) Relationships between surface growth strain and some tree, wood and sawn timber characteristics of *Eucalyptus cloeziana*. *Southern African Forestry Journal* **186,** 41–49.

Nicholson, J.E. (1971) A rapid method for estimating longitudinal growth stresses in logs. *Wood Science and Technology* **5,** 40–48.

Plomion, C., Pionneau, C., Brach, J., Costa, P. and Bailleres, H. (2000) Compression wood-responsive proteins in developing xylem of maritime pine (*Pinus pinaster* Ait.). *Plant Physiology* **123,** 959–969.

Raymond, C., Kube, P., Bradley, A., Savage, L. and Pinkard, L. (2002) *Evaluation of Non-Destructive Methods of Measuring Growth Stress in* E. globulus: *Relationships between Strain, Wood Properties and Stress*. CRC-SPF Technical Report 81, Hobart.

Saurat, J. and Gueneau, P. (1976) Growth stresses in beech. *Wood Science and Technology* **10,** 111–123.

Schacht, L., Garcia, J.N. and Vencovsky, R. (1998) Variação genética de indicadores de tensão de crescimento em clones de *Eucalyptus urophylla*. (Genetic variation of growth stress indicators in clones of *Eucalyptus urophylla*). *Scientia Forestalis* **54,** 55–68.

Specht, R.L., Specht, A., Whelan, M.B. and Hegarty, E.E. (1995) *Conservation Atlas of Plant Communities in Australia*. Southern Cross University Press, Lismore.

Swain, T.L., Gardner, R.A.W. and Chiappero, C.C. (2000) *Final Results of Three ICFR* Eucalyptus dunnii *Trials in Kwazulu-Natal, South Africa*. Institute for Commercial Forestry Research Bulletin 02/2000, pp. 1–15.

Yang, J.L. and Hunter, A.J. (2000) Is curvature adjustment necessary in growth strain measurement? *New Zealand Journal of Forest Science* **30,** 332–340.

Yang, J.L., Fife, D. and Matheson, A.C. (2001) Growth strain in three provenances of plantation-grown *Eucalyptus globulus* Labill. *Australian Forestry* **64,** 248–256.

Yang, J.L., Fife, D., Waugh, G., Downes, G. and Blackwell, P. (2002) The effect of growth strain and other defects on the sawn timber quality of 10-year-old *Eucalyptus globulus* Labill. *Australian Forestry* **65,** 31–37.

Yang, J.L., Bailleres, H., Okuyama, T., Muneri, A. and Downes, G. (2005) Measurement methods for longitudinal surface strain in trees: a review. *Australian Forestry* **68,** 34–43.

Yoshida, M. and Okuyama, T. (2002) Techniques for measuring growth stress on the xylem surface using strain and dial gauges. *Holzforschung* **56,** 461–467.

Yoshida, M., Okuda, T. and Okuyama, T. (2000) Tension wood and growth stress induced by artificial inclination in *Liriodendron tulipifera* Linn. and *Prunus spachiana* Kitamura f. *ascendens* Kitamura. *Annals of Forest Science* **57,** 739–746.

Yoshida, M., Ohta, H., Yamamoto, H. and Okuyama, T. (2002) Tensile growth stress and lignin distribution in the cell walls of yellow poplar, *Liriodendron tulipifera* Linn. *Trees — Structure and Function* **16,** 457–464.