Tension wood occurrence in *Eucalyptus globulus* Labill. II. The spatial distribution of tension wood and its association with stem form

Russell Washusen

[1]CSIRO Forestry and Forest Products, Clayton South, Victoria 3169, Australia
Email: Russell.Washusen@csiro.au

Revised manuscript received 15 April 2002

Summary

To develop rapid non-destructive methods of sampling for tension wood, the spatial distribution of tension wood, diagnosed by high shrinkage in solid wood samples, was assessed in ten, 11-y-old trees from the Mt Gambier region of South Australia.

Selection of the trees was based on the occurrence of gelatinous fibres, an indicator of tension wood, in the most recently-formed wood in four core samples taken from each tree at breast height. In three of the trees the samples had no gelatinous fibres, while the remainder showed a varying incidence of gelatinous fibres.

The selected trees were felled and sample discs were cut at eight points along the stem. Tension wood was predominantly restricted to the lower 30% of tree height and increased in extent and severity toward the base. Only one tree had no significant tension wood, while two had tension wood in the base although no gelatinous fibres were evident at breast height. The results suggest that breast-height cores would be moderately successful in detecting trees with tension wood; core sampling from lower in the stem should be considered for future studies.

The tree-form factor (the ratio of stem volume : volume of a cylinder with the same base diameter and height) was calculated and a shrinkage index was determined to express the extent of tension wood distribution near the stem periphery. The shrinkage index was significantly negatively correlated with the form factor and taper between the base and 5% and 10% of tree height, indicating a greater degree of buttressing in trees with abundant tension wood. This result suggests that in the plantation examined the form factor and the degree of buttressing in the stems were of diagnostic significance for tension wood and may prove useful for tension wood detection in unthinned plantations.

Keywords: reaction wood; stem form; *Eucalyptus globulus*

Introduction

Tension wood is an important wood property that is very common in *Eucalyptus globulus* (Washusen and Ilic 2001). It can profoundly affect solid wood processing through development of growth-stress-related defects during sawing or through drying defects on boards during drying. Tension wood is a reaction wood of hardwoods and is a mechanism for maintaining optimum stem alignment; it generally occurs in discrete bands surrounded by normal wood.

Tension wood is often characterized by the presence of gelatinous fibres in which the secondary wall has been highly modified and lignin is almost absent or absent; with microscopic examination the wall appears gelatinous. Tension wood has high transverse shrinkage in comparison to the surrounding normal wood and, unlike collapse in normal wood, the shrinkage cannot be recovered by steam reconditioning. This characteristic high transverse shrinkage after reconditioning produces corrugations in wood, making detection of tension wood at that time relatively easy, but it is difficult to detect in green wood.

In earlier work Washusen *et al.* (2002a) developed methods for assessing the occurrence, severity and spatial distribution of tension wood, using its characteristic high shrinkage. These methods allow the spatial distribution of tension wood associated with high shrinkage in solid wood samples to be assessed in plantations and in a greater number of trees. The primary objective of the present study was to use these procedures to determine the spatial distribution of tension wood in selected trees from a plantation.

This study also presented the opportunity to assess some factors that may be associated with tension wood occurrence. In conventional theory, tension wood formation is often linked to the development of high internal bending stresses as a response to externally imposed forces such as gravity or wind (Boyd 1977; Kubler 1988). In straight vertical trees from evenly spaced plantations the source of the bending stresses would be largely restricted to wind, and tall slender trees may be subject to greater bending stresses. In work reported by Washusen and Ilic (2001), the ratio of stem diameter at breast height : tree height was correlated with gelatinous fibre percentages at breast height and no clear relationship was evident. However, the stem diameter : tree height ratio may not be an adequate measure of tree slenderness or shape; a better measure may be the ‘tree-form factor’. The tree-form factor is the ratio of volume of the tree : volume of a cylinder with the same basal diameter and total height (Bruce and Schumacher 1942).

The aim of this study was to assess the distribution of tension wood as a preliminary step in developing non-destructive sampling in standing trees. A second aim was to assess the relationship between the tree-form factor, as defined above, and excessive shrinkage and tension wood occurrence.

Table 1. Mean and standard deviation (SD) of mensuration data at 10 y of age for each provenance for the trees selected for sampling

Attribute	Provenance					
	Jeeralang		Western Tasmania		King Island	
	Mean	SD	Mean	SD	Mean	SD
DBH (cm)	28.4	2.9	25.0	3.4	27.5	2.5
Height (m)	26.6	2.9	30.2	1.8	32.2	3.8
DBH/height ($cm\ m^{-1}$)	1.09	0.11	0.92	0.10	0.94	0.09
BA ($m^2\ ha^{-1}$)	26.6	2.9	30.2	1.8	32.2	3.8

Materials and methods

Tree selection

The plantation used in this assessment is described by Washusen and Ilic (2001). It was a provenance trial of *E. globulus* located near Tarpina in the Mt Gambier region of South Australia (elevation 70 m; location 140°55'E, 37°35'S). Mean annual rainfall is about 700 mm with a winter maximum. The plantation had several provenances with seed sourced from multiple-tree collections. The trial was not randomised; each provenance was planted in a belt consisting of a variable number of rows depending on the number of trees planted. The provenance belts were adjacent to each other to form a contiguous plantation. Spacing between rows was 4.0 m; trees were planted 2.5 m apart along the rows that ran north–south. The plantation had not been thinned.

At age 10 y, core samples were taken from 20 randomly selected, evenly spaced trees of three provenances (60 trees in all). The provenances were Jeeralang, Western Tasmania and King Island. All trees were straight, vertical and dominant as judged by the crown position in relation to the surrounding plantation canopy. No tree was sampled within three rows of the edge of each belt or from the ends of the belts. The selected trees had no live branches or large dead branches in the lower two-thirds of the stem. Straightness and vertical orientation were assessed with a plumb line. Each selected tree was measured for diameter at breast height (DBH 1.3 m above ground) and tree height, and the ratio of tree height to stem diameter was calculated for each tree. In addition, a plot basal area (BA) with each selected tree in the center of the plot was estimated with a Factor 1 basal area wedge to give an indication of competition. The means and standard deviations for the mensuration data for the selected trees of each of the three provenances are given in Table 1.

A single increment core, 12 mm in diameter, extending from the bark to about half way to the pith, was extracted from the northern, eastern, southern and western sides of each tree at nominal breast height, making 240 cores in all. Cores were not taken within 75 mm of a branch stub, or a bump that may have indicated an overgrown branch stub.

The cores were marked with a sample number, tree number, and the cardinal direction of north, east, south or west, and stored in air-tight tubes at 4ºC to prevent them from drying out. Transverse sections 18 µm thick were cut on a microtome, stained with safranin and alcian blue, and permanently mounted. Safranin stains lignin and alcian blue stains cellulose, so the staining procedure produces a contrast between normal and unlignified layers in the fibre wall. Normal fibre walls are stained red (safranin) and the unlignified gelatinous layers in tension wood blue, and thus tension wood can be easily identified microscopically. The number of normal and gelatinous fibres in the outer 20% of the core sample length (the outer 10% of the radius of the tree) was then counted along the centre line of each section, and the percentage of all fibres that were gelatinous was calculated for each sample. In all cases the tissue close to the cambium was avoided to eliminate poorly lignified immature fibres from the assessment. Unlike the assessment described by Washusen *et al.* (2002a), this method does not take into account the degree of development of the gelatinous layer and it is a less effective way of quantifying the severity of tension wood.

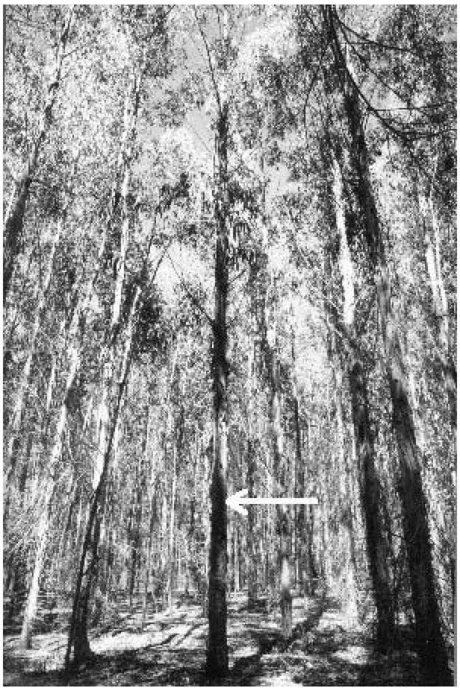

Figure 1. One of the trees selected for harvest

One year after the sample cores were removed (when the trees were 11 y old) ten of the sampled trees from the three provenances were selected for falling, based on the gelatinous fibre percentages in the outer 10% of the radius of trees. An example of the trees is shown in Figure 1. The trees selected varied in the percentage of gelatinous fibres and included three trees in which no gelatinous fibres were observed at breast height. The trees with gelatinous fibres were selected to include three provenances and to span the range of severity of tension wood. Those without gelatinous fibres were randomly selected, one from each provenance. The trees included five from Jeeralang provenance (four with tension wood), three from Western Tasmania (two with tension wood) and two from King Island (one with tension wood). The mean percentage of gelatinous fibres within the outer 20% of the core sample length for each tree, the ranking of tension wood severity for each tree based on the mean percentage of gelatinous fibres, and the individual percentages of gelatinous fibres for each core are given in Table 2.

Table 2. The percentage of gelatinous fibres, determined for the outer 20% of the sample core length (10% of the stem radius) taken at breast height, in trees selected for detailed study (from Washusen and Ilic 2001)

Tree no.	Provenance	Occurrence of gelatinous fibres (%)				
		North core	East core	South core	West core	Mean (rank)
7	Jeeralang	0.0	0.0	0.0	0.0	0.0 (1)
32	Western Tasmania	0.0	0.0	0.0	0.0	0.0 (1)
43	King Island	0.0	0.0	0.0	0.0	0.0 (1)
8	Jeeralang	0.2	3.7	2.3	0.6	1.7 (4)
40	Western Tasmania	0.0	14.0	0.0	0.2	3.6 (5)
19	Jeeralang	18.0	7.7	13.9	10.7	12.6 (6)
5	Jeeralang	21.7	2.9	30.9	3.9	14.9 (7)
56	King Island	0.5	0.0	85.5	12.7	24.7 (8)
28	Western Tasmania	9.4	27.3	84.1	15.9	34.2 (9)
13	Jeeralang	84.6	8.9	10.0	59.8	40.8 (10)

Harvest, disc collection, sample preparation and assessment of tension wood distribution

Except for the minor differences described below, the methods for harvesting, disc collection and sample preparation and assessment of tension wood distribution were the same as those described in the companion paper by Washusen *et al.* (2002a). In that work, shrinkage differentials (S_{SD}) were used to spatially map the distribution of tension wood.

The first difference in method in the present study was in the number of 8 × 8 mm radial strips cut from the discs. The largest discs, those from 0–60% of tree height, were cut into 16 radial strips; those from 70% of tree height were cut into eight strips and the disc from 80% of tree height was cut into four strips using a single, fine-toothed circular saw. The radial strips were measured and dried to 12% moisture content and reconditioned in steam, and the tangential shrinkage was calculated as previously described. From the calculated tangential shrinkage values, the S_{SD} for each radial zone on each radial strip was calculated and used to map the distribution of tension wood.

The second difference was in the anatomical assessment of tension wood presence or absence. In this case tension wood was confirmed by randomly selecting measuring sites within each tree and examining microtome sections stained with safranin and alcian blue. This assessment was limited to 100 samples and no quantification of tension wood severity was attempted from the anatomical sections because of the tedious nature of such an assessment. In each tree where shrinkage differentials were 5.0% or greater, gelatinous fibres were found in all samples, and gelatinous fibres were found to generally appear when shrinkage differentials were between 3.1 and 5.0%, although some isolated and/or thin-walled gelatinous fibres were evident in some samples with shrinkage differentials <3.0%. Thus high shrinkage differentials could be used to approximate the distribution of tension wood and reduce reliance on anatomical methods.

As before, the shrinkage differentials were categorized into four classes: 0–3.0% (to represent normal wood), 3.1–5.0% (the transition from normal wood to tension wood with numerous gelatinous fibres), 5.1–10.0% (tension wood) and >10.0% (severe tension wood), and plotted on spread sheets to produce charts of each whole tree that approximated the tension wood distribution within the tree stems.

Tree-form factor and the relationship with shrinkage differentials

Tree volume was determined by first summing the volumes for the sections of each tree between each pair of discs. The volume of each section was calculated using the mean diameter of the discs at each end of the section. The volume of the top section of the tree (above 80% tree height) was determined using the average of the diameter at the 80% height and zero. The form factor was then determined.

In addition a 'shrinkage index' was determined for each tree by calculating the number of radial strips in the lower 30% of tree height with shrinkage differentials of 3.1% or greater in the outer 75–100% of the radius. The shrinkage index was used in this way to indicate how widespread tension wood was at or near the stem periphery. A Pearson correlation was calculated between tree shrinkage index and form factor and taper from the base to a number of percentage tree heights in a correlation matrix. Pearson correlations were also calculated between the shrinkage index and the ratio of tree height : stem diameter, and tree height and stem diameter separately.

Results and discussion

Spatial distribution of tension wood

An example of a whole-tree chart of shrinkage differentials is shown in Figure 2. The height of each disc is shown at the top of the chart, the location of each radial strip in the standing tree is at the left of the chart, and each radial zone with the radial distance from the pith is given for each disc. Each data cell has been shaded from white to black depending on the category of shrinkage differentials given in the key at the bottom of the chart. For example, cells with a shrinkage differential category of >10.0% are shaded black, indicating that these sections of the radial strip contained severe tension wood.

In all the trees where tension wood was found, high shrinkage differentials were generally restricted to the lower 30% of tree height, mostly in the outer 75–100% radial zone, and increased in severity towards the base. At the base, high shrinkage differentials were more common in the inner two radial zones than in the corresponding radial zones higher in the stem. Isolated zones with high shrinkage differentials were occasionally observed

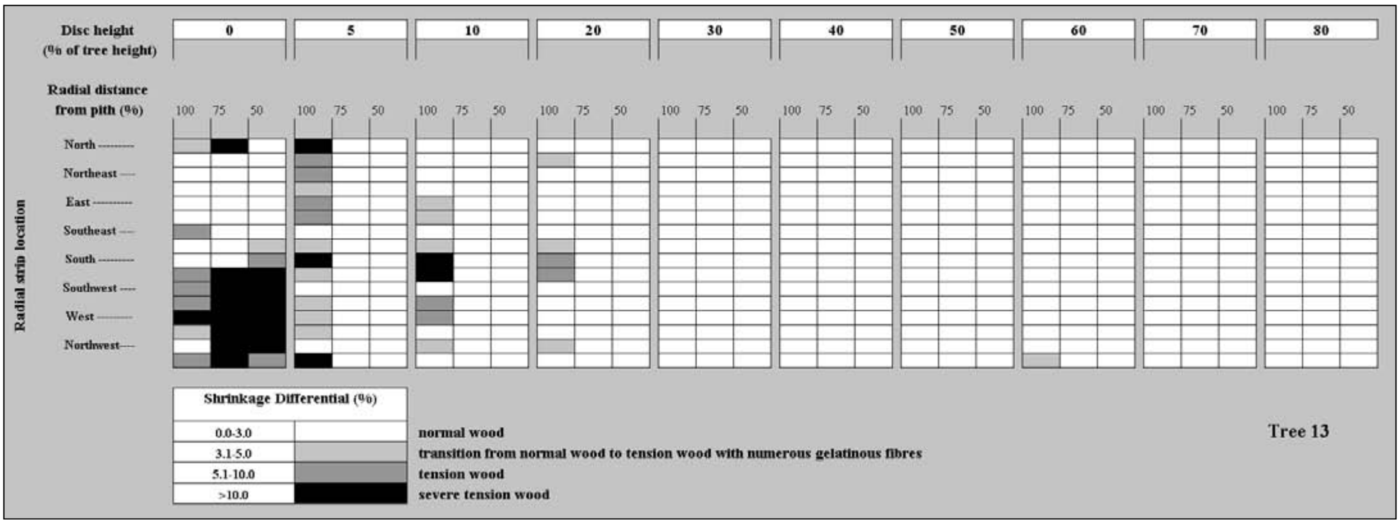

Figure 2. Whole-tree chart of shrinkage differentials for Tree 13

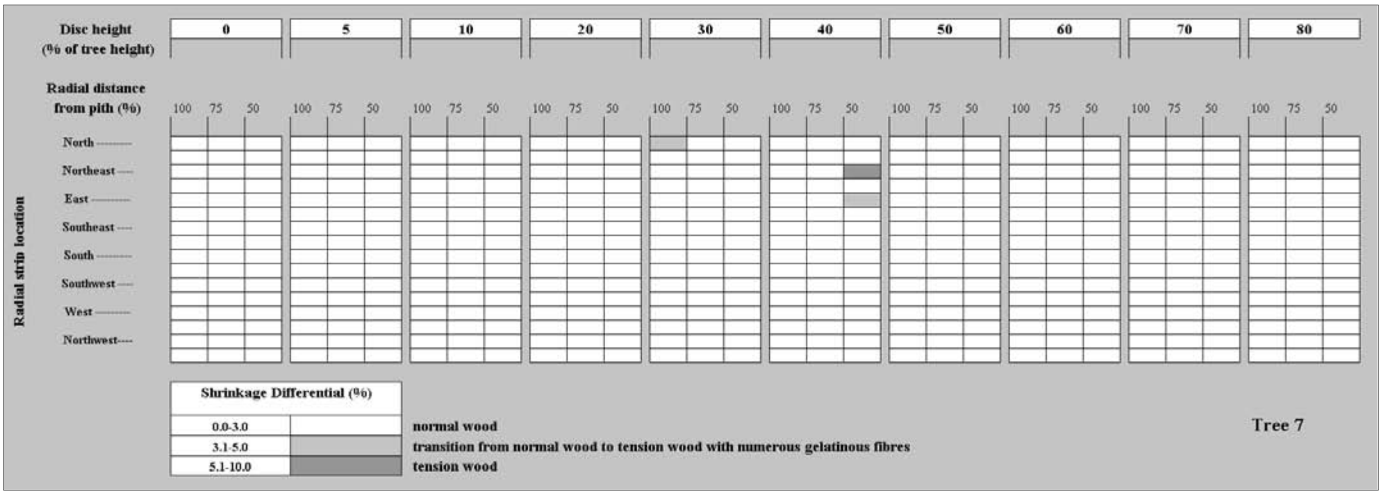

Figure 3. Whole-tree chart of shrinkage differentials for Tree 7

above 30% tree height, but they were usually located close to the pith. In the three trees (Nos 7, 32 and 43) selected on the basis of the absence of gelatinous fibres at breast height, high shrinkage differentials were evident elsewhere in the stem. Thus tension wood was more common in these stems than the breast height cores revealed. In one of these trees (Tree 7 in Fig. 3), some tension wood was found at 40% tree height close to the pith, and a single isolated zone with a few gelatinous fibres (confirmed by anatomical assessment) was found near the stem periphery on the north side of the stem. Other than these two zones this tree was largely devoid of tension wood and displayed little variation in shrinkage. In the other two trees (Nos 32 and 43), high shrinkage differentials were evident at the base of the stems and Tree 32 had an isolated zone with a high shrinkage differential at 10% tree height. In Trees 8 and 40, where small percentages of gelatinous fibres were observed in the core samples (Table 2), shrinkage differentials were low at breast height. Therefore there are limitations to the use of shrinkage differentials to locate tension wood, or alternatively, the definition of tension wood may be called into question. Where little shrinkage occurs in the presence of gelatinous fibres, the fibres are usually thin-walled and have thin gelatinous layers, and/or they may be isolated and scattered among normal fibres. In these circumstances tension wood does not produce high shrinkage after reconditioning and it behaves like normal wood. This type of tension wood may be of little commercial importance because of this similarity, and so there is little need to detect it. Given these exceptions, and in the absence of other methods for rapid detection, shrinkage in small wood samples using the drying procedures employed in this and earlier work (Washusen *et al.* 2002a) appear to be reasonably effective for revealing tension wood in *E. globulus*.

Effectiveness of a sampling strategy at breast height

The results suggest that a sampling strategy that extracted cores at breast height would not detect all trees with significant tension wood. Only the five highest-ranked trees for tension wood severity (Table 2) had shrinkage differentials of 3.1% or greater in at least two of the four strips at the cardinal directions at breast height. On the other hand, tension wood could not be detected by breast height cores in three trees because it was located below that height.

Zones of high shrinkage in the basal disc

The occurrence of zones with high shrinkage differentials in the basal disc suggests that tension wood can be found in most trees

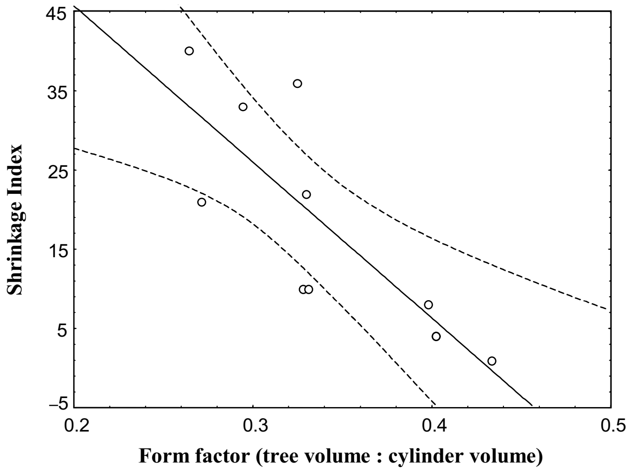

Figure 4. Relationship between the form factor and shrinkage index. The 95% confidence limits are shown.

when grown under the conditions present in the plantation studied. The apparent difference in tension wood occurrence at breast height may simply be an expression of the severity of tension wood formation. Where tension wood is less well developed, it is restricted to the lowest parts of the tree, and extends around and up the stem as severity increases.

In most of the trees the zones of high shrinkage differentials at the base also tended to extend from close to the pith out to the cambium, and so tension wood could be found even in very young trees. Tree 7 had relatively uniform shrinkage in the basal disc, and the uniformity extended to the rest of the tree (Fig. 3), suggesting that screening for basal tension wood may be useful in plantations of any age. There may have been numerous trees in this plantation with little tension wood development near the base, as the selection methods were biased towards trees with significant tension wood development.

The best sampling strategy to detect tension wood in the ten trees in this plantation would have been a combination of breast height and basal cores, 50% of the radius in length, taken from the south-western direction. In this case all nine trees with significant tension wood development would have been detected. Other strategies would have been less effective. For example, if cores equal in length to 50% of the radius were taken at the base, in each of the cardinal locations, then seven of the nine trees would have been detected. A combination of cores taken from the north and south at breast height and from the base would have detected eight of the nine trees. These results highlight the sporadic nature of tension wood development that was shown in Figure 2, and suggest some difficulty in developing accurate methods of detection and in identifying trees with significant tension wood. In other locations, with a different prevailing wind or a sloping site, this strategy would need to be reviewed.

Tree-form factor and shrinkage relationships

The results of the Pearson correlation between the shrinkage index and the tree-form factor gave a coefficient of $r = -0.800$ ($P<0.01$). These data are plotted in Figure 4. In comparison the stem diameter : height ratio gave a correlation of $r = +0.034$, and similar correlations were obtained with diameter at breast height and total tree height alone. This result suggests that one of the factors associated with differences in tension wood occurrence was the form of the trees, and that the simple measures of stem diameter, tree height and the ratio of the two were ineffectual predictors.

In order to assess the relationship between the shrinkage index and stem taper, a Pearson correlation matrix was calculated between the shrinkage index and the stem taper from the base to 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70% and 80% of tree height. The best correlations were with 5% and 10% height, confirming observations that the taper was most pronounced between the base and 5% height. The Pearson correlation coefficients were $r = -0.834$ and $r = -0.831$ (both $P<0.01$) for 5% and 10% heights, respectively.

The nature of the taper of the trees is illustrated in the tree half-stem profile diagrams in Figure 5. It shows the stem shape, using the diameters recorded for each disc as a percentage of the diameter of the basal disc. To accentuate the stem profile, only half of the tree is shown, so that the right side of each diagram is the central axis of the tree and the left side represents the tree profile. The trees are also ranked according to the form factor, from the highest at the left to lowest at the right. As the form factor declined, buttressing low in the stems was more pronounced, taper in the lower part of the stem increased and the upper part of the trees became progressively more slender in comparison to the base. Taper is most pronounced between the basal disc and the 5% height (breast height) in several trees. Trees with the smallest form factor, on the right, had most tension wood, as indicated by the correlation results.

The half-stem profile diagrams also show the approximate zone within which tension wood (determined from shrinkage differentials of 3.1% or greater) was distributed in the lower 30% of tree height. The radial thickness of the tension wood zone is plotted adjacent to the stem periphery, which is the left-hand edge of each tree diagram. Because of the sporadic nature of tension wood distribution the tension wood overlay is a compilation of the tension wood distribution around the stem. The diagrams illustrate the progressive confinement of tension wood to the base of the stems as the form factor increases.

As buttressing is a mechanism for strengthening the lower stem and root system to maintain stem stability, it is understandable that there is an association with tension wood. However, the cause of the differences in tension wood distribution and buttressing is not clear.

One of the main causes for tension wood formation are phototropic effects whereby stems are realigned to maximize the capacity of the trees to receive light. In terms of phototropic effects, there is no obvious reason why, in this study, there should be a correlation between stem form and tension wood distribution at the stem periphery, because all trees had been selected as straight, vertical, dominant and evenly spaced. The selection would have tended to eliminate phototropic effects that cause tension wood to form in suppressed or leaning trees. Moreover, if phototropic effects were a cause, then tension wood may have been more common high in the stem as the position of the crown was progressively altered to make the maximum use of available light.

To see if reorientation or realignment of the stem at the base was associated with tension wood occurrence, disc records were

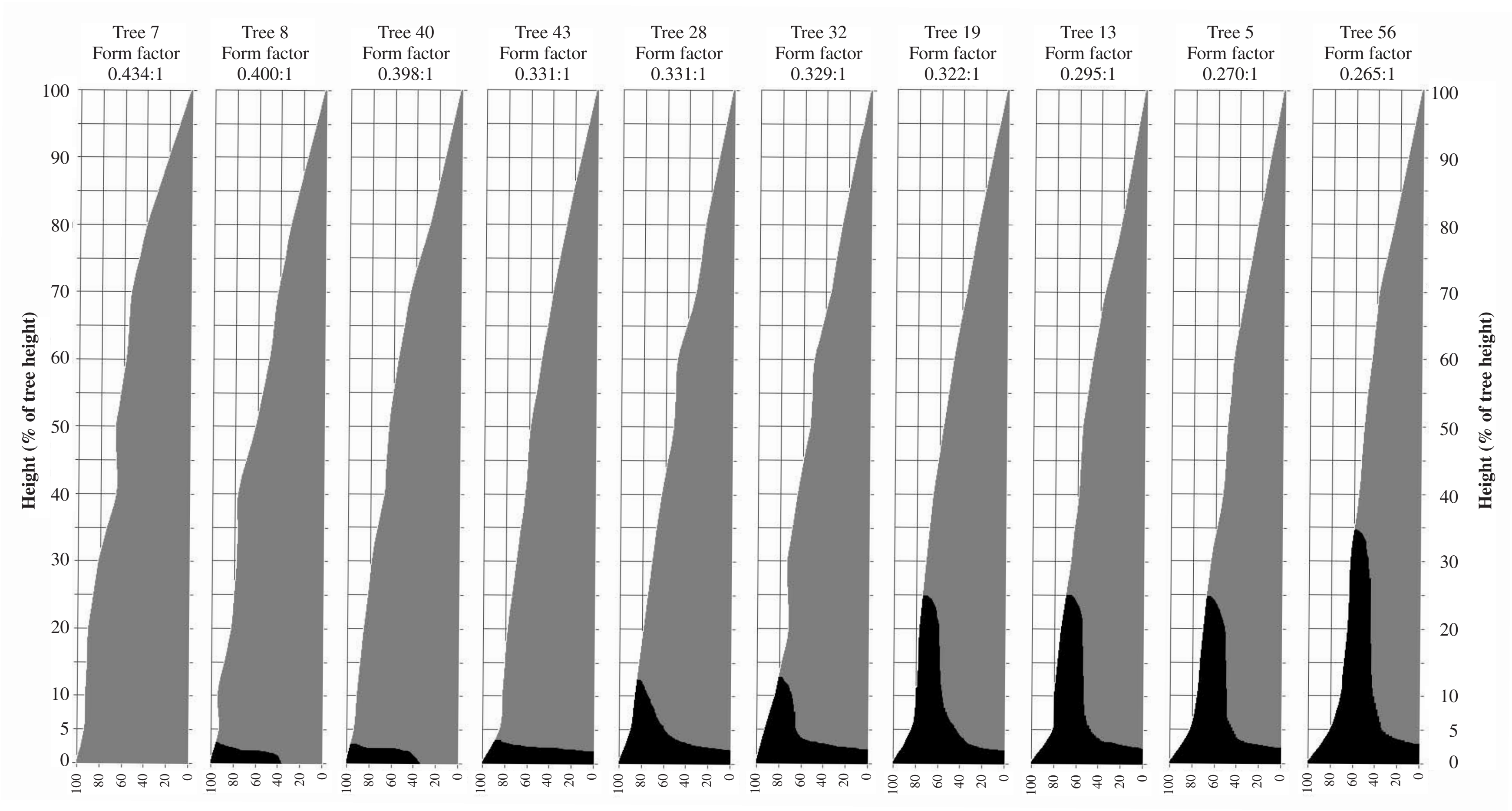

Figure 5. Half-stem profile diagrams for each tree ranked from the highest (left) to lowest form factor (right). Also shown is an overlay of the distribution of tension wood (the dark zone) in which the thickness of the tension wood zone is a percentage of the radius of the tree.

Table 3. The individual plot basal area and form factor for each tree showing the inverse relationship present within each provenance group

Tree number	Provenance	Basal area (m^2 ha^{-1})	Form factor
7	Jeeralang	25	0.434:1
8	Jeeralang	25	0.400:1
19	Jeeralang	26	0.322:1
13	Jeeralang	27	0.295:1
5	Jeeralang	29	0.270:1
40	Western Tasmania	27	0.398:1
28	Western Tasmania	31	0.331:1
32	Western Tasmania	32	0.329:1
43	King Island	29	0.331:1
56	King Island	35	0.265:1

examined to see if the distribution of tension wood near the base of the stems was associated with stem eccentricity. While some minor eccentric growth was evident, there was no clear association of it with tension wood on the faster-growing side of the stem, which is where the tension wood should be if it had formed as a reaction wood to realign the stems. In some cases tension wood had even formed on the opposite side of the tree.

Wind and the development of high bending stresses at the stem periphery may be a possible cause. As discussed above, the more common occurrence of tension wood on the south-western side of the stems, which is the direction of the prevailing wind in the Mt Gambier area, suggests that wind may be the primary cause. The confinement of tension wood to the base of the trees, or at the most the lower 30% of tree height, supports this concept. During windy periods the upper part of the stems may bend considerably, stretching and compressing newly-formed wood tissue at the stem periphery near the base of the tree. The stretching and compression may then trigger tension wood formation and be responsible for buttressing in the stems.

As shown in Table 1, at age 10 y, the trees selected for core-sampling were tall and slender, a condition in which bending moments due to wind would be increasingly significant. An anatomical assessment of wood tissue in an associated study (Washusen *et al.* 2002b) found that, during the year that elapsed between the time that the core-samples were taken and when the trees for the present study were harvested, in several trees gelatinous fibres developed at the stem periphery where no gelatinous fibres were observed in tissue laid down the previous year. This suggests that the conditions within this plantation that had produced tension wood prior to the core sampling had intensified during the subsequent year and fits with a situation where trees had become progressively taller and more slender. Another factor that may have contributed to the variation in tension wood severity may be variation in the degree of protection from the prevailing wind that the selected trees received from neighbouring trees. While the canopy depth was similar in all of the trees because of the method of selecting them, the relative exposure of the crowns to wind was not assessed and should be considered in future work.

There may also be an association between tension wood severity and competition with neighbouring trees. The 10 trees in this study were selected from across a large plantation in which growing conditions and competition between trees varied, and thus there is difficulty in making comparisons within the group. However, within each of the provenance groups the plot basal area, measured at each tree at the initial core sampling, increased as the form factor declined (Table 3), supporting the notion that there is a connection between inter-tree competition and tension wood formation. If competition between trees was reduced, tension wood occurrence may also be reduced.

Implications of the sample size and tree selection

The small sample size and the nature of the selection process (whereby trees were selected on the basis of the presence of gelatinous fibre at breast height) limits the extrapolation of the results to the rest of the trees in this plantation. Future studies should expand on this research, using a larger number of trees to assess the distribution of tension wood at plantations at different sites, with different silvicultural backgrounds and genetic origins (including other species of eucalypts). This could be done by core-sampling low in the stem, from the direction of the prevailing wind and considering the aspect of the plantation, and then using information from the cores to choose trees for harvesting to assess the distribution of tension wood.

Conclusions

Apart from some minor tension wood development high in the stems and usually close to the pith, tension wood was predominantly restricted to the lower 30% of tree height. Low in the stem, tension wood tended to be located near the stem periphery, suggesting that it had only recently formed at these locations. In some trees tension wood completely encircled the stems while in others it was more sporadic, leading to difficulty in developing sampling or detection strategies. In all trees tension wood increased in severity towards the base, and it also formed closer to the pith near the base than higher in the stem; in several trees, it had formed in each of the three radial zones in the basal disc. In general, the distribution was similar to that recorded in the previous study of one tree from East Gippsland.

These results suggest that core-sampling at breast height would be only moderately successful at detecting tension wood, as two of the three trees that had no tension wood at breast height had tension wood at the base. The greater incidence of tension wood near the base suggests that sampling lower in the stem may be warranted. This is supported by the fact that the one tree with no tension wood in the base had little tension wood higher in the stem. Overall, the distribution of tension wood suggests that a sampling strategy that extracted cores from the south-west direction at the base and at breast height would have been effective at identifying all trees with significant tension wood development. Tension wood in these trees may have developed in response to the prevailing south-westerly wind; future work should investigate this association further.

Nine of the ten trees had some degree of tension wood formation near the base and in several it began to form early in the growth of the tree, suggesting that trees at risk of tension wood formation may be detected at a younger age than 11 y.

Tension wood occurrence in the outer 75–100% of the radius was correlated with the tree-form factor and taper or the degree of buttressing in the lower part of the stem. Future studies should re-examine this relationship in an attempt to understand why this is the case and to see if silviculture or genetic selection can reduce tension wood formation. Silvicultural research may be particularly important because of the suggested relationship between stand density and tension wood formation found in this and associated studies in this plantation. Information on the form factor or taper may be required, along with a core-sampling strategy, to predict the occurrence of tension wood in plantations that have not been thinned.

Acknowledgements

This research was funded by CSIRO–FFP as a contribution to a Natural Heritage Trust project. The author is grateful to Mr Mick Underdown of ForestrySA who allowed access and sampling in the plantation. Mr Les Scott, Mr Damian Scown and Mr Glen Roberts, all of CSIRO–FFP, assisted in sample collection and preparation. The author also acknowledges Mr Bill Neilson of Forestry Tasmania who suggested that the tree-form factor may be a better measure of stem slenderness than the ratio of breast height diameter to tree height. This paper is partly based on results from a PhD research program conducted by the author at the University of Melbourne.

References

Boyd, J.D. (1977) Basic cause of differentiation of tension wood and compression wood. *Australian Forest Research* **1,** 121–143.

Bruce, D. and Schumacher, F.X. (1942) *Forest Mensuration.* McGraw-Hill Book Company, Inc. New York and London, pp. 307–308.

Kubler, H. (1988) Silvicultural control of mechanical stresses in trees. *Canadian Journal of Forestry Research* **18,** 1215–1225.

Washusen, R. and Ilic, J. (2001) Relationship between transverse shrinkage and tension wood from three provenances of *Eucalyptus globulus* Labill. *Holz als Roh-und Werkstoff* **59,** 85–93.

Washusen, R., Ades, P. and Vinden, P. (2002a) Tension wood occurrence in *Eucalyptus globulus* Labill. 1. The spatial distribution of tension wood in one 11-year-old tree. *Australian Forestry* **65,** 120–126.

Washusen, R., Ilic, J. and Waugh, G. (2002b) The relationship between longitudinal growth strain and the occurrence of gelatinous fibres in 10 and 11-year-old *Eucalyptus globulus* Labill. (submitted). *Wood Science and Technology.*