VARIABILITY IN STEM WOOD PROPERTIES DUE TO BRANCHES*

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ABSTRACT

A stem and branch growth model, TreeBLOSSIM, has been developed for *Pinus radiata* D. Don that predicts the location and diameter of branches adjacent to the stem on an annual basis. Research is under way to extend the model to predict wood properties in three dimensions: vertically with increasing tree height, radially with increasing tree age, and circumferentially around a growth ring.

Four studies were carried out to examine the role that branches may have in influencing the 3-dimensional variability of wood properties. These studies illustrated how wood fibres were arranged in the vicinity of a branch, and how the stem cross-sectional shape varied through a cluster of branches; and they indicated that the wood properties in the internode below a branch cluster may be influenced by the diameter of the branches.

Keywords: branching; fibre arrangement; wood properties; *Pinus radiata.*

INTRODUCTION

The arrangement of branches within the tree crown, and foliage distribution on these branches, influence the amount of light intercepted by the foliage (e.g., Whitehead *et al.* 1990). This in turn influences the amount of photosynthate available for growth.

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Branches also contribute to the variability in wood properties within the stem in several ways. The arrangement of wood fibres around the branch-stem junction (Shigo 1985) is one source of variability; this leads to reduced strength and stiffness in the vicinity of a branch (knot) within a piece of timber (e.g., Phillips *et al*. 1981).

There is also evidence that branches influence the properties of wood in the internode below the branches. Nicholls (1986) examined the variation in basic density along the length of six *P. radiata* internodes. There were no significant differences along four of these internodes, but basic density of samples taken close to branch clusters in the other two could be up to 5% higher than that of samples taken from near the middle of the internode. Based on this and other published studies, Nicholls (1986) concluded that wood immediately adjacent to branch clusters and extending approximately 20 cm away may have higher density, shorter tracheid lengths, and disturbed grain angles.

This paper summarises four small studies that examined how branches may influence the 3-dimensional (3D) variation in wood properties in *P. radiata*. The first study examined how wood fibres were arranged at the branch-stem junction. The second study examined how the presence of branches altered the stem cross-sectional shape. The third and fourth studies examined how wood properties varied in the section of stem (internode) below a branch cluster.

These studies provided knowledge that will be used in extending TreeBLOSSIM, a distance-independent model of stem and branch growth for *P. radiata* (Grace *et al.* 1998, 1999), to predict the 3D distribution of wood properties as a function of tree and, in particular, crown development.

STUDIES OF BRANCH INFLUENCE ON WOOD PROPERTIES

1. Fibre Arrangement Around Branches

Methods

The objective of this study was to determine whether the fibre arrangement around branches, proposed by Shigo (1985), was appropriate for *P. radiata*. Shigo’s research indicated that branches are attached to the stem by an alternating series of “branch collars”, formed early in the growing season, and “trunk (stem) collars”, formed later in the growing season.

The *P. radiata* branch clusters used for the current study were collected from near the top of felled trees. They were at least 1 year old (i.e., old enough to show both branch and trunk collars), and had a stem diameter of approximately 40 mm and branch diameters of approximately 10 mm. In order to isolate one branch, samples were cut vertically into quarters, and then horizontally to leave 20 mm of stem above the branch and 30 mm below the branch.

A chloriting treatment was used to remove the lignin in the samples and allow the fibres to be separated. In order to find the most effective chloriting method a number of variations were tested starting from methods described by Kibblewhite (1969). The following treatment produced the most useful result. The fresh wood sample was placed in a beaker and immersed in sufficient hot water to cover it (200 ml), then glacial acetic acid (3 ml) and technical grade sodium chlorite (7.5 g as $NaClO_2$) were added. The same amount of acid and chlorite was added daily for 5 days. The sample was then left soaking for at least 1 week. The beaker was covered and heated on a steam bath to 70°C, with the temperature kept constant for 1 hour before another dose of the same amount of chemicals was added. This process was repeated each hour for a further 2 hours.

Results

This chloriting treatment led to lignin removal through the entire sample, and permitted the sample to be dismantled. It was apparent that the branch (9 mm in diameter) was completely separate from the rest of the sample, and there was a continuous layer of fibres under the branch (Fig. 1). Also visible (on the left of the image) was an area of swelling around the branch that was made up of stem fibres displaced by the branch. An additional two samples subjected to the same chloriting treatment confirmed the arrangement of fibres visible in Fig. 1. The fact that the branch could be completely separated from the surrounding stem with no evidence of "branch" and/or "trunk (stem)" collars suggests that the structure for the branch-stem junction, proposed by Shigo (1985), does not hold for *P. radiata*.

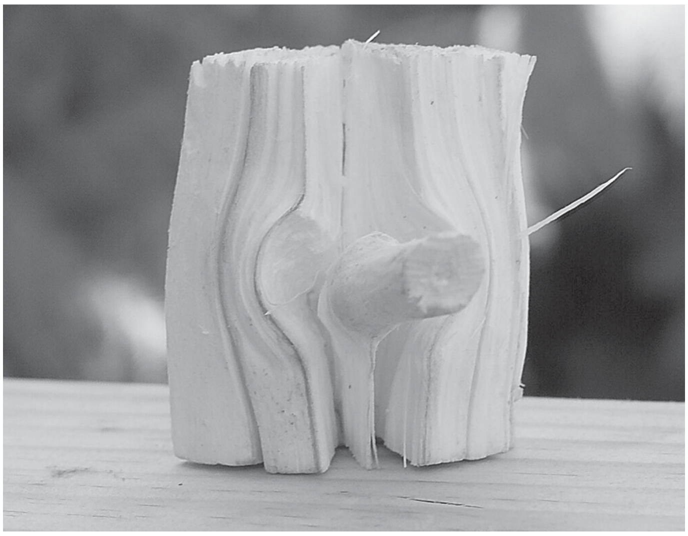

FIG. 1–Image showing delignified and separated stem-branch junction. The branch is 9 mm in diameter.

2. Stem Cross-sectional Shape in the Vicinity of Branches

Methods

The arrangement of fibres in the vicinity of branches leads to some swelling of the stem (*see* Fig. 1). The objective of this study was to determine how stem cross-sectional shape varied in the vicinity of a branch cluster. In December 2002, one cluster with four branches was selected from a nominally straight *P. radiata* planted in 1975. The branch cluster was 29 m above ground level. Seven complete growth rings (i.e., latewood bands present) and the current season's growth ring were present. The position of the latewood bands (rings 1–7), and the edge of the stem (ring 8) were recorded using a Coordinate Measuring Machine (CMM) located at the University of Canterbury, Christchurch.

A stand was made to hold the branch cluster and ensure that its position remained unaltered in the CMM. Starting at the top, the outline of the outside edge of the stem and each latewood band was digitised. A 2-mm cross-sectional slice was then removed. The process was repeated for over 60 slices. The data were imported into Solidworks and a 3-dimensional model of the stem section was created.

Results

Several images of the modelled stem section were created (Fig. 2). Longitudinal surface roughness apparent on the model was considered due to "aliasing" introduced when fitting continuous surfaces to discrete measurement data. Latewood bands visible on longitudinal/radial stem surfaces showing branch-stem junctions were much smoother (Grace *et al.* 1999). The surface of the latewood bands, rings 1–7 (a–g), and the stem edge, ring 8 (h) around one of the branches, are shown in Fig. 2. In the first ring, the branch–stem junction appeared smooth. In later rings a hollow developed immediately adjacent to the branch, with some possible swelling of the stem around the hollow. This hollow had almost disappeared by ring 8. The complete cluster can be seen in Fig. 2i with a wedge removed to show the interior arrangement of growth rings around branches. These models correspond with features observed on planed branches, and it is considered that these features are related to the vigour of the branch.

3. Quantitative Variation in Wood Properties within Internodes

Methods

As part of a study to explore the influence of the tree crown on stem wood properties, one branch cluster and the internode below were selected from each of five nominally straight 11-year-old *P. radiata* trees planted at 250 stems/ha and left unthinned. Criteria used in the selection were: clusters towards the base of the tree with larger than average branches and a longer than average internode below the cluster (Table 1).

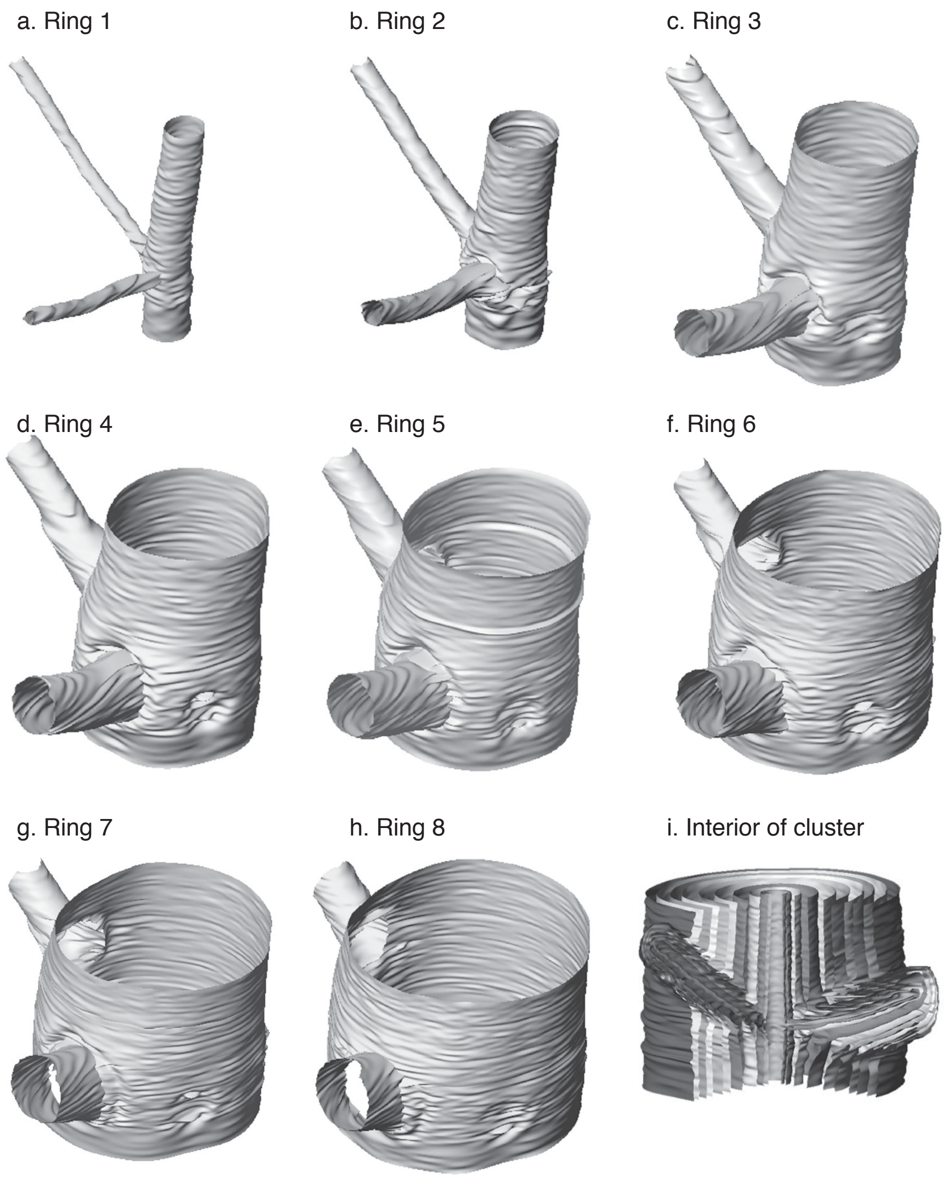

FIG. 2–Models showing the shape of each latewood band for growth rings 1 to 7 (a–g), stem edge (ring 8), and the complete cluster (i) with a wedge removed to show the interior of two branches. The exterior diameter of the cluster was approximately 190 mm.

The internodes were too heavy to carry out whole from the forest, so it was decided to cut and carry out a wedge running the length of the internode for further analysis. The disadvantage of this approach was that it gave only a limited picture of the circumferential variation in wood properties.

TABLE 1–Characteristics of the branch clusters and internodes selected for Study 3.

Tree	A16	A24	C09	D13	E17
Height to base of branch cluster (m)	5.35	2.97	6.09	6.03	5.18
Maximum branch diameter (mm) in cluster	93	67	61	75	44
Branch basal area (mm^2) in cluster	17 404	14 207	7 742	18 057	6 342
Length of internode (m)	0.48	0.42	0.35	0.62	0.36
Angle between SilviScan strips (degrees) (to nearest 10°)	80	30	60	40	30

In the laboratory, slices were cut from the stem wedges. The top 2 cm nearest the branch cluster were discarded, and then the following was repeated to the base of the internode. The next 2 cm were saved for cutting samples for SilviScan analysis (Evans *et al.* 2001) and the following 4 cm were discarded (6 cm for tree D13).

In each of the slices saved for SilviScan analysis, two strips were marked (one set below a large branch and the other at an angle — Table 1), and images were taken. The marked strips were analysed for density (at 50 mm resolution) and microfibril angle (at 5 mm resolution) using SilviScan (Evans *et al.* 2001). The SilviScan data were summarised to ring average values. Strips that did not include the pith often contained an incomplete growth ring. Such rings were excluded from the following analysis. For each growth ring in each tree, the variation in density and microfibril angle was calculated as the difference between maximum and minimum values divided by the mean value, and expressed as a percentage.

Results

Visually, one internode contained little or no compression wood. This internode (from tree E17) was the one with the smallest maximum branch diameter and smallest branch basal area in the cluster above. Visually, three internodes contained patchy or solid compression wood that extended the length of the internode. These internodes were from trees A16, C09 (Fig. 3), and D13, and included the tree with the largest maximum branch diameter in the cluster above. Visually the internode from tree A24 contained patchy compression wood in the top two but not the lower layers.

The variation in ring average density (Fig. 4) was generally less than 20%. It tended to be higher for tree D13, the tree with the largest branch basal area in the cluster above. Tree E17, the tree with the smallest branch basal area in the cluster, tended to have the lowest value in a given year. The high variation for Tree E17 in the 1996–97 growing season was a consequence of the narrow ring width and the difference in ring width from top to base of the internode. The variation in ring average microfibril angle (Fig. 5) was generally less than 30%. Tree E17 tended to show the

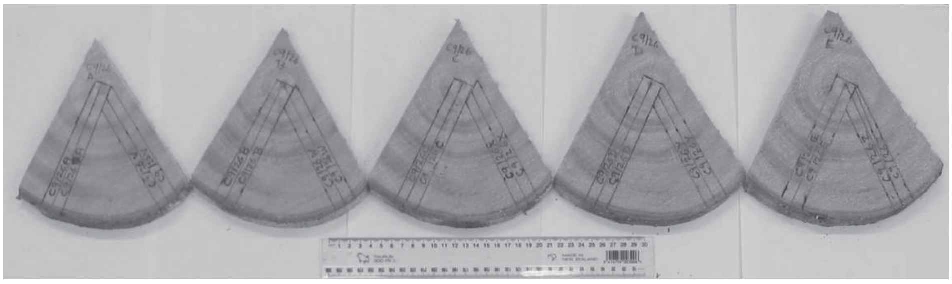

FIG. 3–Samples marked for SilviScan analysis from Tree C09. The left-hand slice was 2 cm below the base of the branch cluster. Each subsequent slice was 6 cm below the previous one. The two marked strips on each slice were analysed using SilviScan. Only one strip per slice included the stem pith.

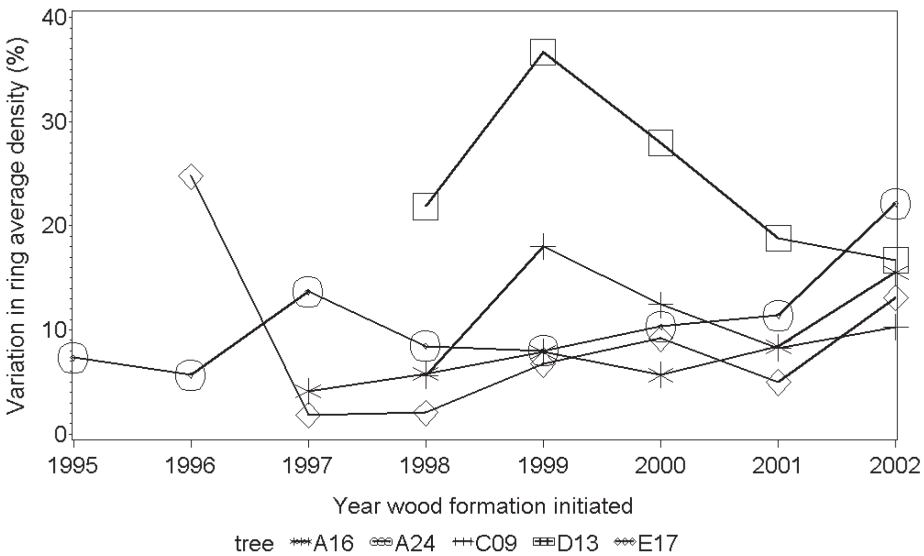

FIG. 4–Percentage variation in ring average density across samples from the same internode and formed in the same growing season.

least variation in a given year. The variation for tree D13 tended to decrease with increasing age, whereas the variation tended to increase for trees A16 and C09.

4. Visual Variation in Wood Colour through Internodes

Methods

The previous study provided quantitative data on the possible magnitude of variation in wood properties within an internode, but it was surprising that the visible compression wood generally extended throughout the length of the internode.

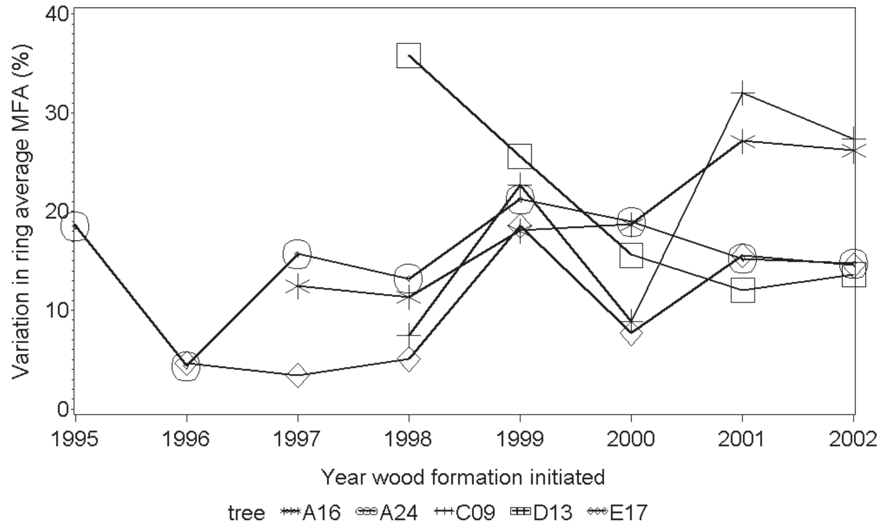

FIG. 5–Percentage variation in ring average microfibril angle (MFA) across samples from the same internode and formed in the same growing season.

It was considered that a better qualitative understanding of the variability was needed before any more quantitative studies were carried out.

As part of a study to examine the influence of tree growth on stem wood properties, twenty 14-year-old *P. radiata* trees were felled from a genotype × silviculture experiment. There were two trees of average diameter at breast height (1.4 m) from each of 10 treatments.

One aim was to obtain a series of disc images at approximately 6-cm intervals throughout the internode below selected branch clusters in the lower third of the crown. Clusters containing large branches and clusters containing small branches were selected. Discs were orientated with respect to each other and the corresponding branch cluster by means of a reference line, painted along the length of the felled stem.

Results

The final data set included sequences of images throughout 21 internodes, and images of discs cut immediately below a further 11 branch clusters, giving 32 images of discs cut immediately below branch clusters. These 32 images were examined and the position of the branches in the cluster was overlaid. The maximum branch diameter in the cluster above ranged from 13 mm to 74 mm (generally smaller than in the third study). Thirteen of the images showed signs of compression wood that appeared to be related to branch position whereas the others showed no obvious signs of compression wood. Qualitatively, it appeared that compression wood was more likely to be visible on discs immediately below clusters with large branches (Fig. 6). Internodes below clusters where the maximum branch diameter was less than 40 mm rarely showed signs of visible compression wood, whereas internodes below clusters where the maximum branch diameter was greater than 60 mm generally showed signs of visible compression wood. Further data will be required to fully explore the relationships between branch diameter, branch position, and compression wood distribution.

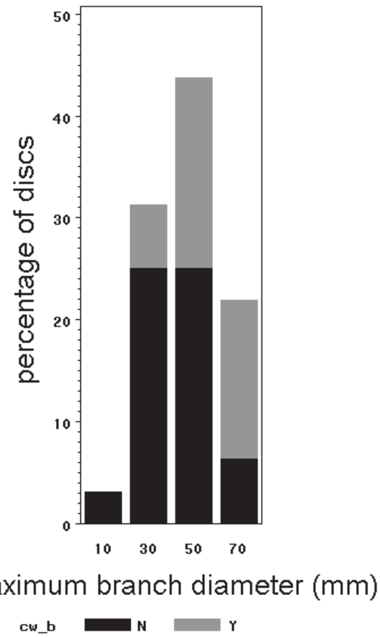

FIG. 6–Percentage discs below branch clusters that showed (cw_b = Y) or did not show (cw_b = N) signs of compression wood in relation to the diameter of the largest branch in the cluster immediately above the disc.

DISCUSSION

The model TreeBLOSSIM was initially developed to predict growth of individual trees and branches from mid-rotation onwards. We are now exploring the possibilities of expanding this model to predict the distribution of wood properties within the stem in three dimensions as a function of tree growth. Predicting the 3D variability is considered essential as it is the variability in wood properties that contributes to problems at the end-use phase. Such a model could be used as input for processing models, and would thus create a link between the growing tree and the performance of the end-product.

The first study described in this paper examined how wood fibres were arranged in the vicinity of branches. We were expecting to confirm the model of Shigo (1985), but our example (Fig. 1) suggests that model does not hold for *P. radiata* as there was no evidence of “branch” and “trunk (stem)” collars. This result indicates that the model of Philips *et al.* (1981), which used laminar flow around an elliptical object as a model of the grain deviation around a branch in the longitudinal-tangential plane, was a realistic simplification.

The second study examined the stem cross-sectional shape in the vicinity of branches and showed that the shape of the growth ring surrounding the branch changes with age. These changes are considered to be related to the vigour of the branch. Knowledge of the orientation is important as wood properties vary radially within a growth ring from earlywood to latewood. Hence, changes in growth ring orientation will influence the distribution of wood properties within a piece of timber.

The third and fourth studies were designed to determine whether, for nominally straight trees, branches had any influence on the wood properties in the internode below. The fourth study showed that visible compression wood rarely occurred in internodes below clusters where the maximum branch diameter was less than 40 mm, whereas visible compression wood was generally present in internodes below clusters where the maximum branch diameter was greater than 60 mm.

The internodes measured in the third study were from trees at wide spacing, and the maximum branch diameter in the cluster above ranged from 44 mm to 93 mm. These internodes generally contained visible compression wood. Wood density and microfibril angle varied by up to 40% between different samples from the same growth ring. This variation was much greater than suggested by Nicholls (1986). Further studies are required to confirm that these results are generally applicable, and to be able to quantify the variability in a cost-effective manner.

With regard to the development of a model that predicts the observed variation in wood properties within an internode, Larson (1969) commented that wood formation is an integral part of tree growth and cannot be studied independently. Other comments from Larson (1969) include: compression wood can be produced by applying high levels of synthetic auxin, indole-3-acetic acid (IAA), to *P. resinosa* Aiton (red pine) stems; the most vigorous shoots with their developing needles appear to be the principal source of auxin for tracheid enlargement; under the influence of wind sway, steeper gradients of auxin may be produced in the stem. It is therefore possible that the compression wood observed in the internodes below clusters with large branches is a result of auxin gradients within the tree.

Current modelling approaches that are worth considering in the process of developing a model to predict the 3-dimensional variability in wood properties include: TreeRing (Fritts *et al.* 2005) that predicts the development of a radial file of cells from a tree physiology perspective; the AMAP modelling system (e.g., Fourcaud *et al.* 2003) that predicts stem development from a biomechanical perspective; and the work of Kramer that models growth as a function of auxin (Kramer 2001, 2002; Kramer & Borkowski 2004) .

Development of TreeBLOSSIM to incorporate 3-dimensional variability in wood properties requires consideration of current modelling approaches, analysis of applications for the model, and further data collection on within-stem variability in wood properties.

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