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Impact of thinning and pruning on selected wood properties in individual radiata pine trees in New Zealand

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Abstract

Trees are complex living organisms that are continuously laying down new cells with a structure appropriate for survival (including mechanical reliability) in their current environment. Trees need to adapt to new environmental conditions following silviculture operations and one adaptive response is alteration of their wood properties. This study examines how wood density and microfibril angle in individual radiata pine (*Pinus radiata* D.Don) trees changed in response to seven different pruning and thinning regimes.

Pith-to-bark wood samples were taken from just above stump height (approx. 0.3 m above the base of the tree) in 28-year-old trees that were part of a silvicultural experiment. Ring-average values of wood density and microfibril angle were obtained using SilviScan-3.

A comparison of these radial profiles indicated that severe pruning, together with moderate to heavy thinning resulted in an increase in microfibril angle around the time of thinning which interrupted the commonly observed downward trend in microfibril angle with increasing ring number from the pith. Most trees showed an increase in ring-average wood density in the year following the final thinning, however this may be related to environmental conditions rather than thinning as the increase also occurred in the untreated control.

Near the end of the rotation, average microfibril angle and average wood density for rings 21 to 26 were not influenced by the historic silvicultural treatments.

These results support our understanding that the developmental history of a tree must be taken into account when estimating the overall wood structure and properties and that tree DBH alone is insufficient.

Keywords: microfibril angle; pruning; radiata pine; thinning; wood density.

Introduction

Trees are complex living organisms. Larson (1962, 1969) considered a tree to be an integrated system where both growth and wood properties depend on the photosynthetic capacity of its crown. The photosynthetic capacity is controlled by genetics and prevailing environmental conditions (Larson, 1962; Megraw, 1985). In addition, trees need to be mechanically reliable, and adjust their mechanical properties through the addition and structure of new cells (Wilson & Archer, 1979).

Both tree flexure (when the tree moves in response to wind and returns to a vertical position), and lean correction (which occurs when a stem has been "permanently" displaced from the vertical) contribute to varying cell structures. In particular, microfibril angle

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has been observed to increase in tracheids formed under the influence of flexure (Telewski, 1989). As microfibril angle increases, wood becomes more flexible and the risk of breakage is lowered (Quine & Gardiner, 2007; Lachenbruch et al., 2011). Asner and Goldstein (1997) showed that tree species with more flexible stems (quoted as lower modulus of elasticity) were able to shed wind loads and thus reduce stem breakage. In contrast, Cameron and Dunham (1999) found that the modulus of elasticity was lower in snapped stems compared to undamaged stems of a similar size for both Scots pine (*Pinus* sylvestris, L.) and Sitka spruce (*Picea sitchensis* (Bong) Carrière). In their study, wood property information was obtained from defect-free outerwood specimens between 0.8 and 1.3 m above ground level, rather than close to the point of stem breakage, where it is likely that the defect-free wood properties were different. Additionally, failure may have been initiated by some "strength-limiting defect" such as a branch cluster, which increases the probability of breakage (Quine & Gardiner, 2007).

In New Zealand, heavy thinning and live-branch pruning of radiata pine (*Pinus radiata* D.Don) were recommended in the 1980s to produce high quality sawlogs in a financially efficient manner (James, 1990). Silvicultural operations alter the tree's local environment in various ways, including reducing the opportunity for wind damping by crown-to-crown contact. One would, therefore, expect to observe altered wood properties following silviculture as the tree develops new cells to make it mechanically reliable in its new environment. However, adaptation lags rapid changes in environmental conditions. Consequently, there is a temporary increase in the risk of stem breakage and windthrow (Gardiner et al., 2000), which is particularly high in the first two years after thinning (Ainsworth, 1989).

As well as altered cell properties, there may be changes in the allocation patterns to roots. Santantonio and Santantonio (1987) found that fine-roots accounted for 4.6% and 6.1% of total dry matter production in control (closed-canopy) and heavily thinned stands of radiata pine, respectively. Lopez et al. (2003) found an increase in fine root production in thinned compared to control plots of holm oak, *Quercus ilex* L. There was a change in allocation favouring coarse roots over stems following tree removal in white spruce (*Picea glauca* (Moench) Voss) stands (Urban et al., 1994).

Within even-aged radiata pine stands, there is likely to be considerable variation in the local numbers of stems per hectare. So potentially, at the end of the rotation, one could find trees of the same DBH (diameter at breast height) in areas with different local numbers of stems per hectare. An important question is whether such trees have similar wood properties, i.e. are final tree dimensions (in this case tree DBH) sufficient for predicting wood properties, or is it necessary to know the developmental history for each tree?

To address this question, two wood properties (ring-average microfibril angle and ring-average density) were examined for trees selected from a 2.5-ha trial area that was scheduled for clearfelling. The trial area contained seven Permanent Sample Plots (plots) that had received different thinning and pruning treatments. These plots were from the high site-quality area within a uniform precision, second-order fully rotatable response design in three dimensions (Myers, 1971), that investigated the effects of thinning and pruning on the growth of radiata pine over a range of site qualities in Hawkes Bay, New Zealand (Goulding & Inglis, 1990). In the following text, "plot" is equivalent to "treatment".

Methods

The trial area was located within Mohaka Forest (Latitude: 39.1°S, Longitude: 177.0°E) at approximately 240 m above sea level. The mean annual windspeed, estimated from Easting, Northing and elevation[1], was 8.9 km hr^{-1}. For the individual plots, the slope varied between 3 and 6 degrees and the aspect was recorded as either East or South East. The stand was planted in 1982, at a stocking of 1543 stems ha^{-1}, and the trial was installed when the trees were three years old. Each of the seven plots, which received different thinning (Table 1) and pruning (Table 2) treatments, was routinely re-measured until the trees were 26 years old.

Trees were selected for this study based on their DBH. The DBH measurements taken when the trees were 26 years old were ranked in ascending order and the list was examined to find pairs of trees where the DBH difference was 0.5 cm or less. Fifty trees were selected from the 108 trees available. This provided at least one pair of trees from all but one combination of silvicultural treatments. A minimum of five and a maximum of nine trees were sampled in each plot. The mean DBH for the sample trees was close to the mean DBH for the plot (Table 3), and the range of DBH sampled was comparable to the range within the plot.

The area containing the trial was clearfelled in 2009 at the beginning of the twenty-eighth growing season. For those trees selected for further study, a disc (approx. 5 cm thick) was cut from the lower end of the butt log at the time of felling. These discs were located approximately 0.3 m above the base of the tree. This position, rather than breast height, was chosen to

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TABLE 1: Thinning treatments applied.

Plot	Stems ha^{-1} at 3.05 years	Age (years) at first thin	Stems ha $^{-1}$ remaining after first thin	Reduction from stems ha $^{-1}$ at 3.05 years (%)	Age (years) at second thin	Stems ha^{-1} remaining after second thin	Reduction from stems ha^{-1} at 3.05 years (%)	Stems ha^{-1} at 26 years	Reduction from stems ha^{-1} at 3.05 years (%)
1	1259	3.95	598	53	6.05	131	90	131	90
2	1246	3.75	598	52	5.65	137	89	112	91
3	1037	3.40	602	42	6.05	351	66	201	81
4	1221	3.75	602	51	5.15	368	70	268	78
5	1259	3.75	598	53	5.15	131	90	81	94
6	1171	3.95	602	49	5.65	184	84	151	87
7	898	-	-	0	-	-	0	474	47

minimise the loss of value to the forest owner and to obtain a longer sequence of growth rings. The discs were transported to Scion where they were imaged to provide a permanent record.

Four 20-mm wide pith-to-bark strips were marked on the disc surface and then cut from the disc to provide samples for processing through SilviScan-3. The original intention was to cut a bark-to-bark strip through the direction of maximum compression wood and two pith-to-bark strips at right angles, which would enable the within-disc variability in wood properties to be measured. Due to fluting, the presence of branches and other damage to some of the discs, the locations of the four pith-to-bark strips were modified slightly to provide "clean" samples that were free of defects. The four strips tapered to a point at the pith. They were cut down to 20 mm in the longitudinal direction, and soaked in ethanol for one week. The ethanol was then changed and the samples soaked for a further week before air-drying. This procedure reduced the chance of checking and prevented fungal growth. One strip per tree was selected for processing through SilviScan. It was selected to be at right angles to, or opposite any obvious compression wood zone. Additionally, preference was given to strips where the innermost ring was clearly visible. For some trees, a second sample was also processed to ensure that there were no major differences between directions sampled in terms of wood property patterns. The strips were then sent to CSIRO, Clayton, Australia, where they were cut down to 2 mm × 7 mm (tangential × longitudinal dimensions) and processed through SilviScan-3 to give conditioned density (~ 7% moisture) at 0.025 mm intervals and microfibril angle averaged over 5-mm intervals. The raw SilviScan traces for density and microfibril angle for one sample are shown in Figure 1.

Growth ring boundaries were assigned by examining the density profile for each sample. Boundaries were assigned where density decreased rapidly from latewood to earlywood using the G2Ring software (Pont et al., 2007). Boundaries were confirmed visually using an image of the sample. The tree age when each growth ring was formed was determined by visually matching ring width on the SilviScan samples to ring widths obtained from the time sequence of field DBH measurements. This was essential as 28 growth rings

TABLE 2: Pruning treatments applied.

Plot	Length of crown remaining after each pruning (m)	Age (years) at first prune	Mean prune height (m) after first prune	Age (years) at second prune	Mean prune height (m) after second prune	Age (years) at third prune	Final mean prune height (m) after all lifts	Mean pruned height (m) at age 6 years (prior to final thinning)
1	2.5	3.95	1.7	4.40	3.5	5.65	5.4	5.4
2	7.0	5.00	2.1	6.05	4.3	7.25	6.4	2.1
3	2.5	3.40	1.8	4.25	3.4	5.65	5.2	5.2
4	7.0	5.00	1.9	5.65	4.4	6.55	6.2	1.9
5	Not pruned	-	-	-	-	-	-	-
6	Not specified	5.05	4.5	-	-	-	4.5	4.5
7	Not pruned	-	-	-	-	-	-	-

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TABLE 3. Number and DBH of trees in plots and samples.

Plot	Number of trees in plot	Mean DBH (cm)	DBH range (cm)	Number of trees sampled	Mean DBH (cm)	DBH range (cm)
1	21	69.8	46.5 – 97.0	8	72.1	46.5-97.0
2	18	74.7	46.9 – 92.1	6	67.4	46.9-82.4
3	12	53.7	37.2 – 72.7	5	56.1	38.7-63.0
4	16	57.1	34.2 – 82.6	8	59.1	39.3-82.6
5	13	82.3	55.9 – 106.2	7	78.5	55.9-97.5
6	9	67.0	35.3 – 82.9	7	71.8	60.0-82.9
7	19	44.2	26.2 – 68.3	9	44.7	26.2-68.3

were not visible on some discs. For example: tree 6 in plot 1 (Figure 2), increased only 1.2 cm in DBH between 16 and 26 years, and depending on the direction, no more than 14 or 19 growth rings could be distinguished on the SilviScan density traces for this tree. Ring-average microfibril angle (MFA) and ring-average density were calculated for each identified growth ring. The ring-average values of MFA are unreliable when the ring width approaches the sampling interval of 5 mm. The incomplete growth rings at the beginning and end of each strip were excluded from the following analysis.

The silvicultural operations occurred over a number of years (Tables 1 and 2). Values of ring-average MFA and ring-average density prior to any silviculture treatment were not available for all samples so it was not feasible to account for pre-treatment differences between trees. As the final thinning operation was at approximately 6 years for all plots (Table 1), relative MFA and relative density were calculated by dividing the ring-average value at a given age by the ring-average value of the growth ring at age 6-years. Graphs of relative MFA, and relative density versus tree age were visually examined to determine trends both at a plot level and for individual pairs. Differences between treatments were observed following the final thinning, but the differences diminished with time. Based on these visual trends, metrics that would quantify the observed differences in the first few years after final thinning were developed. The selected metrics were:

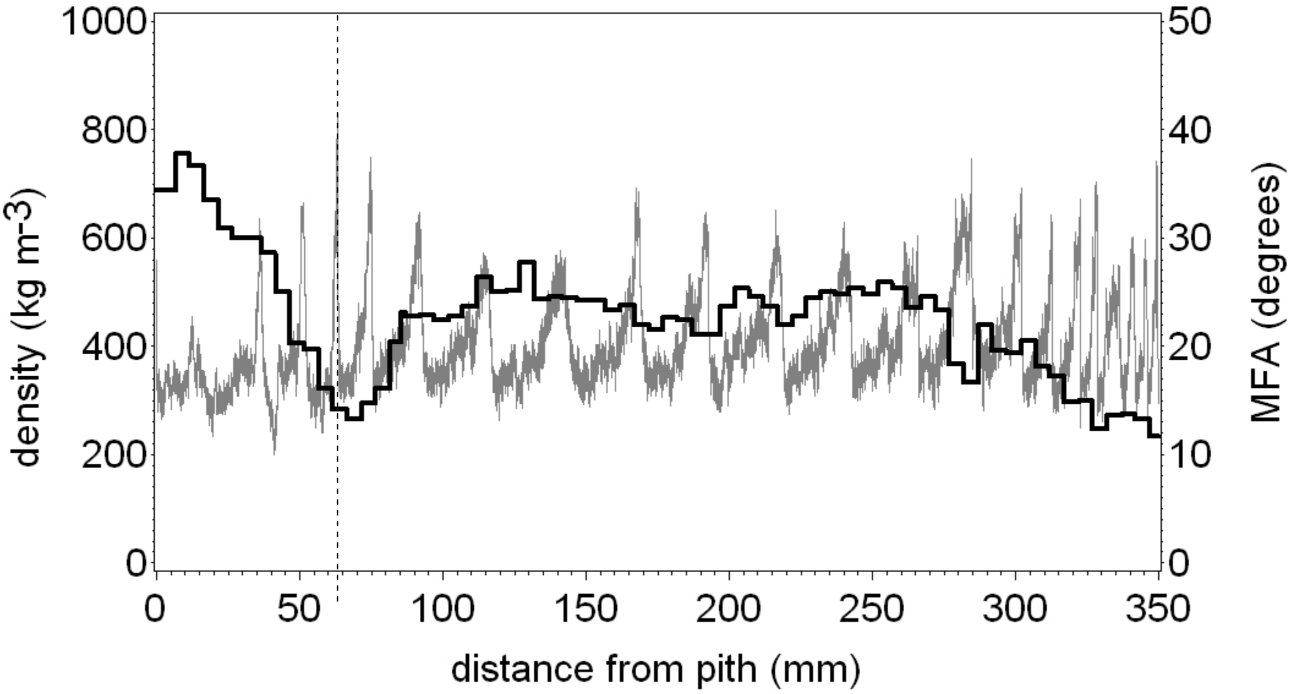

FIGURE 1: Radial profiles of wood density (0.025 mm intervals; grey line) and MFA averaged over 5.0 mm intervals (black line) for one sample. Note this sample shows an increase in ring width, decrease in density range and increase in MFA lasting for several years after the second thinning treatment. Position of the second thinning is marked with a dashed line.

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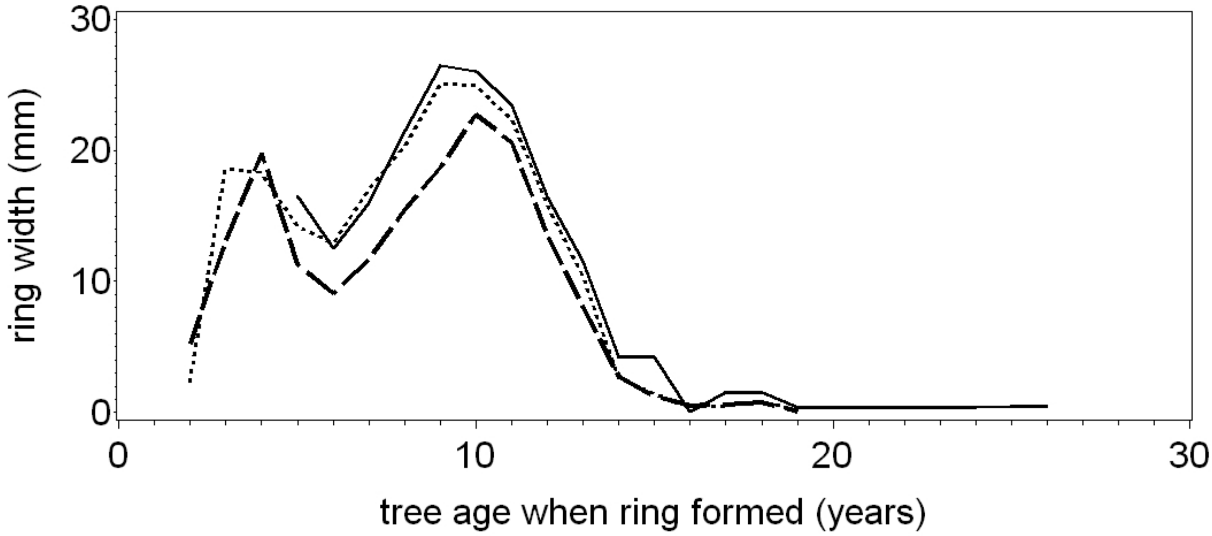

FIGURE 2: Graph illustrating differences in ring-width data obtained for tree 6 in plot 1. The two dashed lines (----- and ·······) show widths determined from two SilviScan strips. The solid line was obtained from field data.

Ring-average density at age 7 years – ring-average density at age 6 years (D7-6) [1]

and

Ring-average MFA at age 10 years – ring-average MFA at age 7 years (MFA10-7) [2]

The influence of tree DBH at age 26 years and treatment on the above two variables was examined using the SAS procedure PROC GLM with DBH as a continuous variable and treatment as a class variable. If either variable was not significant, it was excluded and the analysis repeated.

The same procedure was used to determine whether:

- Ring-average MFA and ring-average density at age 6 years had been influenced by silviculture prior to the final thinning.
- Ring-average MFA at age 10 years was influenced by silvicultural treatment.
- End-of-rotation values (MFA and density for rings 21 to 26 years) were influenced by the silviculture treatments. This time interval was chosen to ensure the sample length considered was greater than 5 mm.

For five of the 50 trees sampled (four from plot 7 and one from plot 4), ring width at either 7 years or 10 years was less than 5 mm. The relevant analyses were carried out excluding these trees.

Results

Figure 1 shows the raw SilviScan traces for one sample, and illustrates the increase in MFA that was observed after thinning. Where there was an increase in MFA, some of the samples, such as this one, showed a decrease in the maximum density within the ring. This change in density is not obvious at the ring level in the graphs (Figure 3) which show relative density (ring average density/ring average density at age 6 years) and relative MFA (ring-average MFA/ring-average MFA at age 6 years) versus tree age when the ring was formed for each individual tree. Thinning treatments occurred between 4 and 6 years, and the vertical lines on the graphs highlight this period in the tree's life.

Wood Density

The long-term trend was for relative density to increase with increasing tree age (Figure 3). An obvious feature was the increase in relative density from age 6 to 7 years for most trees. The response was particularly obvious for individual trees in plots 1, 3 and 5. These plots had been thinned heavily to approximately 130 stems ha^{-1}. Based on these trends, the change in ring-average density between age 6 and 7 years was selected to quantify the response after the final thinning.

Ring-average density at age 7 years - ring-average density at age 6 years (D7-6) was generally positive for individual trees from separate plots (Figure 4). Also, there was no obvious relationship between D7-6 and tree DBH at age 26 years for individual trees from

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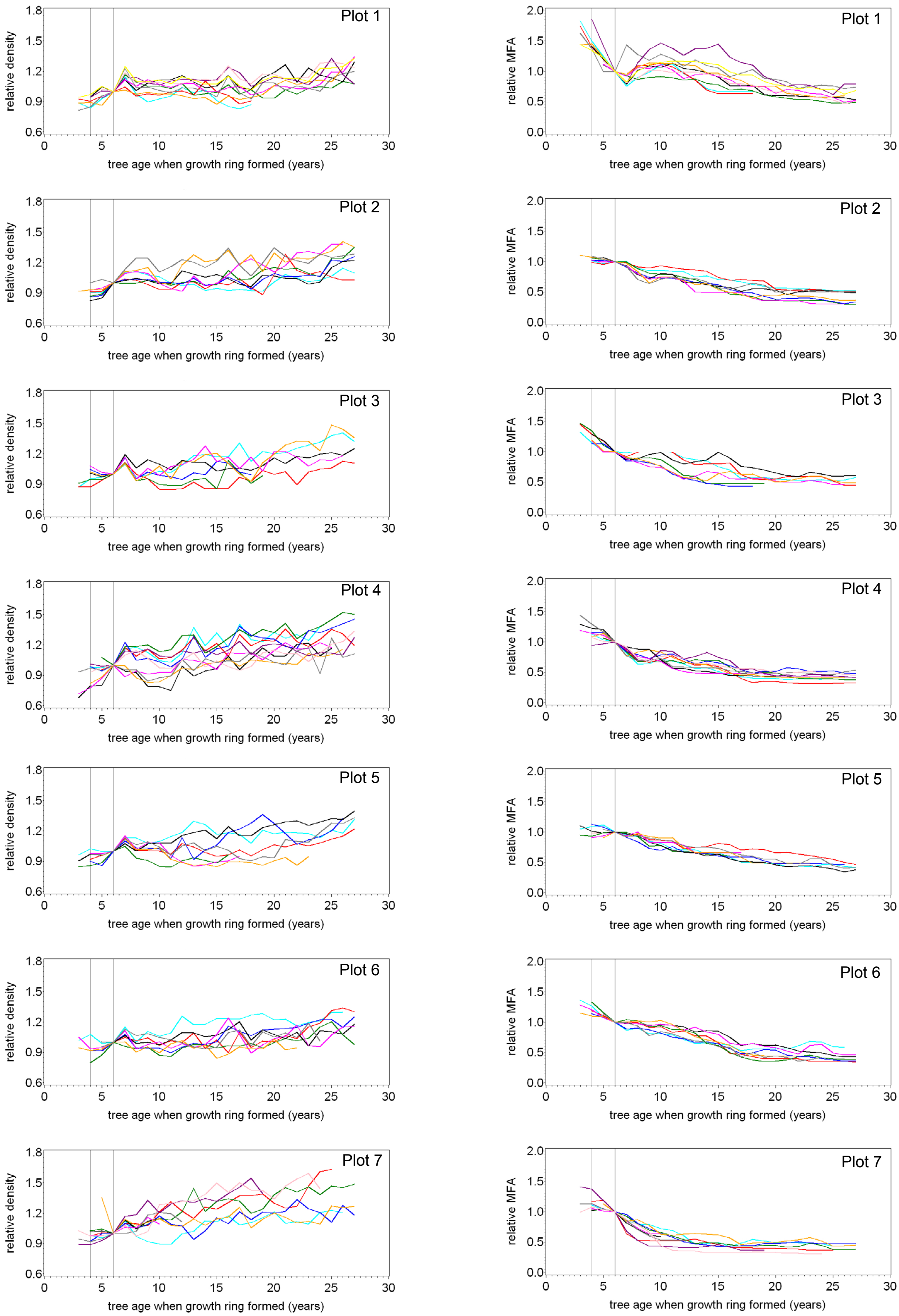

FIGURE 3: Graphs showing relative density and relative MFA of each individual SilviScan sample by plot. Each coloured line represents data from one sample strip. The vertical lines at ages 4 and 6 years represent the times of thinning.

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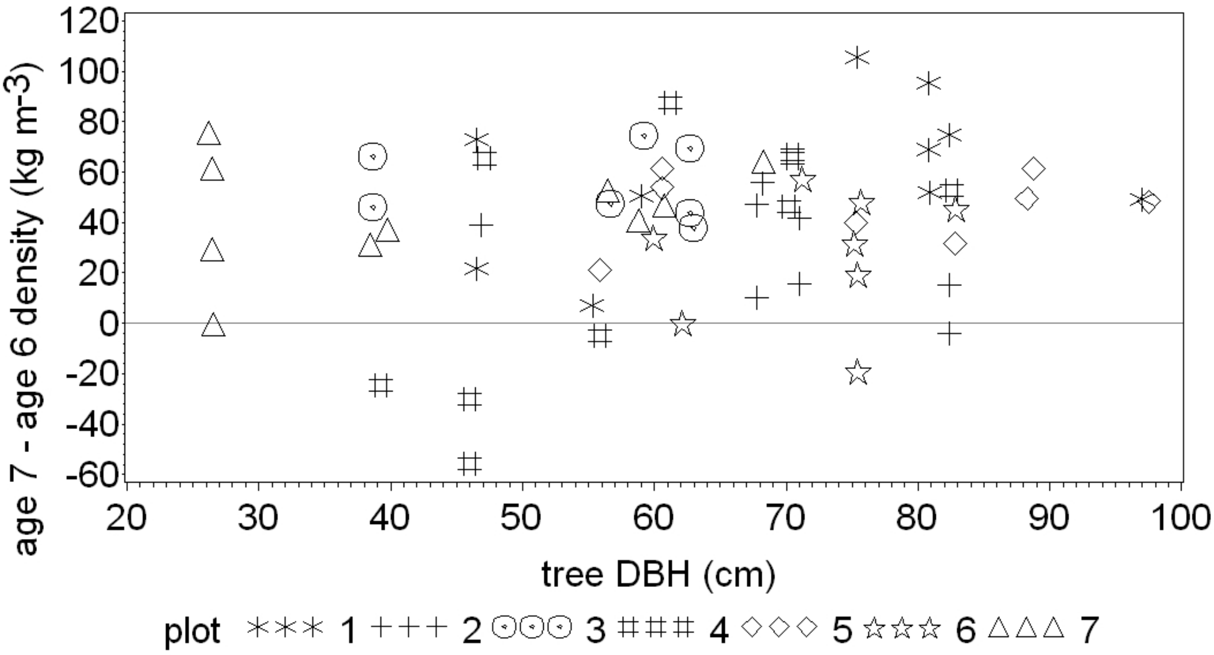

FIGURE 4: Change in ring-average wood density between age 6 and 7 years versus DBH at age 26 years for individual trees in separate plots.

separate plots (Figure 4). This lack of a relationship was confirmed by the SAS procedure PROC GLM. There were a few negative values, in particular from trees located in plot 4. These were trees with a high density at age 6 years.

The SAS procedure PROC GLM indicated that ring-average density at age 6 years (immediately prior to final thinning) was not influenced by either plot or DBH at age 26 years (data not shown).

The average density for rings 21 to 26 in individual trees was not influenced by plot; however there was a slight negative trend with tree DBH at age 26 years (Figure 5). This may not be of practical importance as it was the result of data from two trees with low DBH and high density and two trees with high DBH and low density. The trend was not significant if these points were excluded.

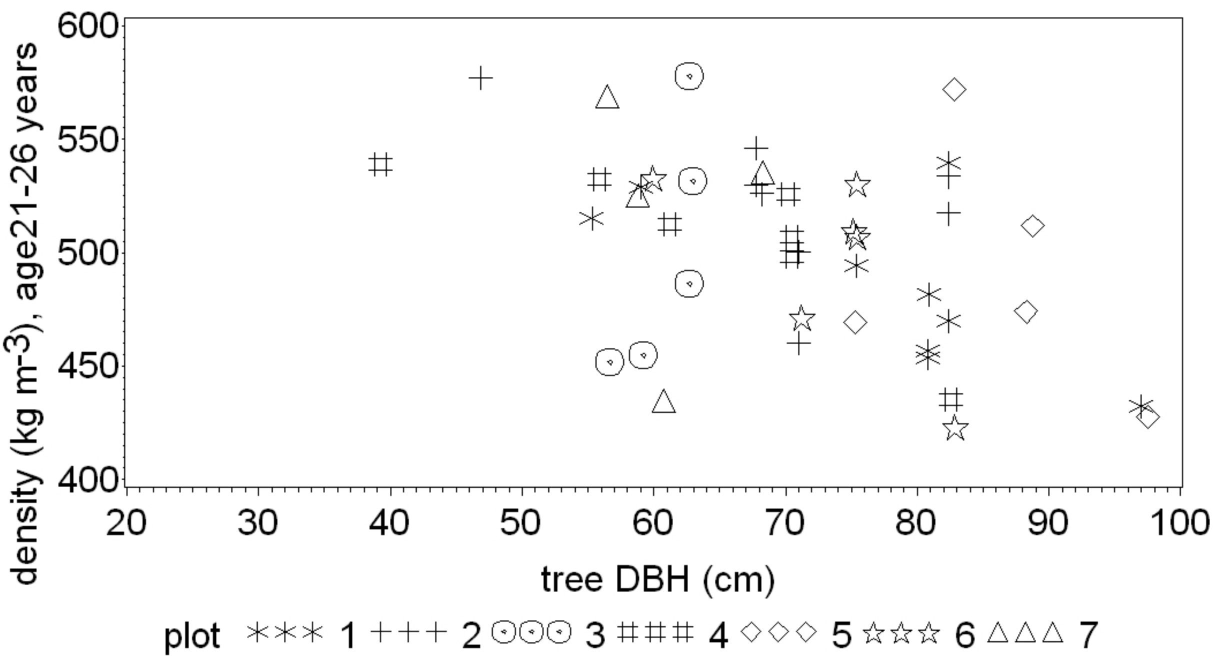

FIGURE 5: Relationship between ring-average wood density for rings 21 to 26 years and DBH at age 26 years for individual trees in separate plots.

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Microfibril angle

Relative MFA generally decreased with increasing tree age (Figure 3). In plot 1 and to a lesser extent in plot 3, relative MFA of individual trees generally decreased at age 7 years and then increased to a maximum around age 10 years before starting to decrease again. Based on these observed trends, the change in ring-average MFA between 7 and 10 years was selected to quantify the response after the final thinning. Plots 1 and 3 had the most severe pruning treatment with 2.5 m of crown remaining after each lift. Also all pruning lifts had been completed by the time of the second thinning (Table 2), which was more severe in plot 1 (131 stems ha^{-1} remaining) compared to plot 3 (351 stems ha^{-1} remaining). In contrast, there was no obvious increase in relative MFA of individual trees in plots 2 and 4 where 7 m of crown was left after each pruning lift. Due to the longer length of crown remaining, the timing of the pruning lifts was later and only one lift had occurred prior to the second thinning (Table 2), There was no obvious increase in relative MFA of individual trees in response to silvicultural treatment in plot 5, which was heavily thinned (131 stems ha^{-1} remaining) but not pruned.

Ring-average MFA at age 10 years – ring-average MFA at age 7 years (MFA10-7) for individual trees was generally negative except for plot 1, where there was an increase in MFA following silviculture treatment (Figure 6). The SAS procedure PROC GLM indicated that there were significant differences between plots (p < 0.0001) but no significant relation with tree DBH at age 26 years. The plot mean value of MFA10-7 was +4.7 degrees in plot 1, +0.1 degrees in plot 3 and negative for all the other plots (Table 4).

TABLE 4: Plot mean values of MFA10-7.

Plot	Mean MFA10-7 (degrees) [1]	Grouping using Duncan test
1	+4.7	A
3	+0.1	B
6	-1.7	BC
4	-3.1	BCD
5	-5.2	CD
2	-5.8	D
7	-9.9	E

[1] *Values listed in descending order.*

At age 6 years (Figure 7a) and age 10 years (Figure 7b), the SAS procedure PROC GLM indicated that there was no significant relationship between ring-average MFA and tree DBH at age 26 years. However there were significant differences in ring-average MFA between plots at both ages (p < 0.0001 and 0.0012, respectively). In contrast to plot mean MFA10-7 values, plot mean ring-average MFA at age 6 years (before the plots where thinned to varying numbers of stems per hectare were lowest for plots 1 and 3 which had received the heaviest pruning, and highest for the unpruned plots (Table 5). At age 10 years, plot mean values of ring-average MFA were higher in plots 1, 3, 5 and 6 that had received the heavier thinning (Table 6).

By the end of the rotation, there were no significant differences in age 21-26 year individual tree values of ring-average MFA between plots and no significant relation with tree DBH at age 26 years (Figure 8).

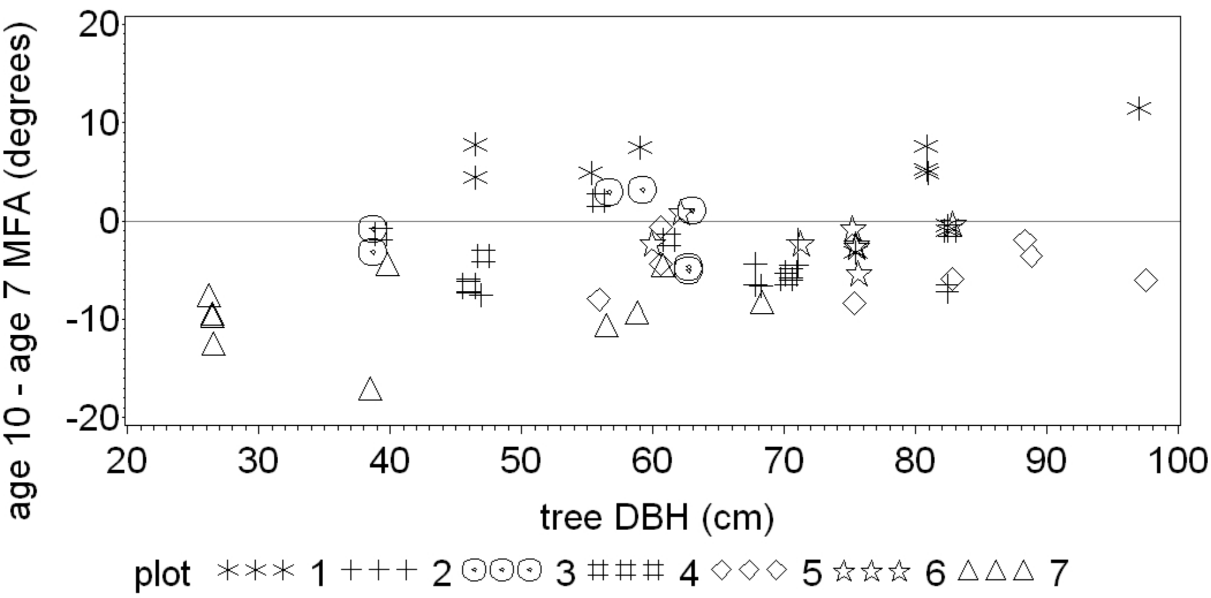

FIGURE 6: Change in ring-average microfibril angle between age 7 and 10 years versus DBH at age 26 years for individual trees in separate plots.

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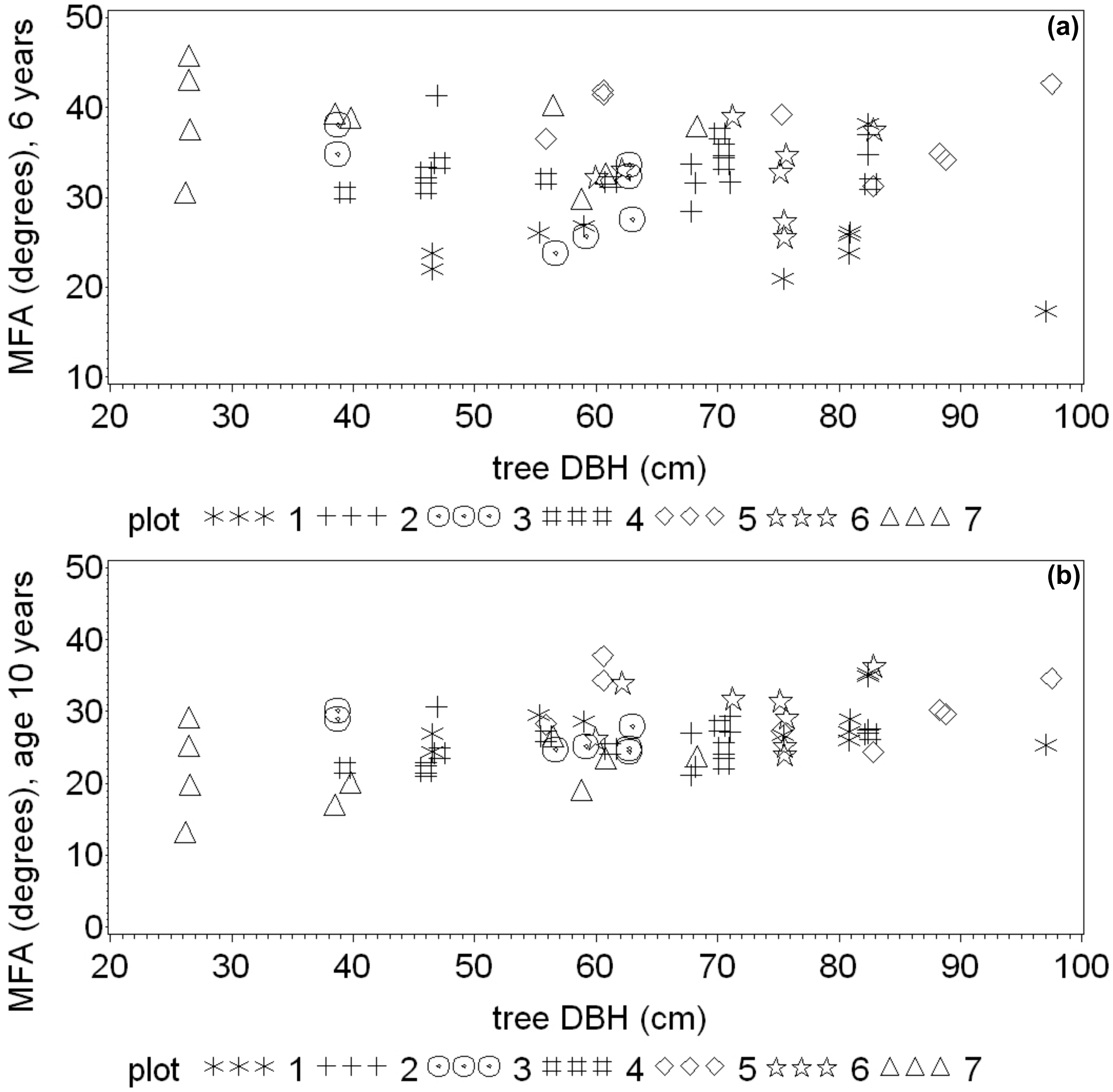

FIGURE 7: Relationship between ring-average microfibril angle at two different ages and DBH at age 26 years for individual trees in separate plots; (a) microfibril angle at age 6 years; and (b) microfibril angle at age 10 years.

Discussion

The objective of this study was to determine whether tree DBH measured prior to harvest would be sufficient information for predicting tree wood properties, or whether knowledge of the tree's history (e.g. silviculture, local numbers of stems per hectare, and/or local environment) is also important.

This issue was addressed by selecting trees of equal DBH from small plots, within a 2.5 ha area, which had received different silvicultural treatments. The method of selection provided a good representation of trees from each silvicultural treatment with the mean DBH of the selected trees being close to the plot mean. However there was no advantage of selecting the trees in pairs when it came to analysing the influence of tree DBH and treatment on selected wood property metrics, and an analysis based on the selected pairs was abandoned in favour of the analysis presented here.

Wood Density

The tendency for density to be low near the pith and increase with ring number towards the bark is well known (e.g. Megraw, 1985). This trend may be explained in terms of the increasing distance from the tree crown, as Larson (1969) indicates that formation of low-density early wood is favoured by proximity to foliage. Conifer wood density may be unchanged, increase or decrease following thinning (e.g. references cited by Zobel & van Buijtenen, 1989; Morling, 2002; Peltola et al., 2007). For radiata pine in New Zealand, either no change (Sutton & Harris, 1974) or a decrease (Cown, 1974) in density have

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TABLE 5: Plot mean values of MFA at age 6 years.

Plot	Mean MFA 6 years (degrees) [1]	Grouping using Duncan test
5	37.2	A
7	36.8	A
6	33.8	AB
2	33.8	AB
4	32.9	AB
3	29.3	BC
1	25.4	C

[1] *Values listed in descending order.*

TABLE 6: Plot mean values of MFA at age 10 years.

Plot	Mean MFA 10 years (degrees) [1]	Grouping using Duncan test
6	30.7	A
5	30.1	AB
1	28.3	ABC
3	26.5	ABC
2	26.1	BCD
4	25.2	CD
7	22.0	D

[1] *Values listed in descending order.*

been observed. Changes in moisture availability at different times during the growing season promoting either earlywood or latewood have been suggested as a reason for the variation (Megraw, 1985; Cregg et al., 1988; Barbour et al., 1994).

The influence of pruning on radiata pine wood density was examined by Cown (1973) for three or four years after removal of 54% or 76% of the live crown respectively. In each case, there were two treatments – no thinning or poison thinning, which would have resulted in a slow change in growing space. Compared to the unthinned and unpruned control, density increased in the first or second year after treatment. In a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) pruning experiment, Gartner et al., 2005) found that when the very lowest live branches were removed there was no effect on wood density but when the pruning removed higher live branches there was a small, short-lived increase in density.

In this current study, trees were both thinned and pruned. Most trees showed an increase in ring-average density between age 6 and 7 years, just after the final thinning, including the untreated control, and there was no clear differentiation between the different silvicultural treatments (Figure 4). As most trees responded similarly, it suggests that the response may be due to environmental conditions rather than the silvicultural treatment. Near the end of the rotation, average density for rings 21-26 decreased slightly with increasing tree DBH, but there were no additional effects of silvicultural treatment.

Microfibril angle

The tendency for ring-average MFA to be high near the pith and decease with ring number from the pith is well known (e.g. Megraw, 1985). The results from this study indicate that silvicultural treatment has a large and complex impact on MFA. At age 6 years

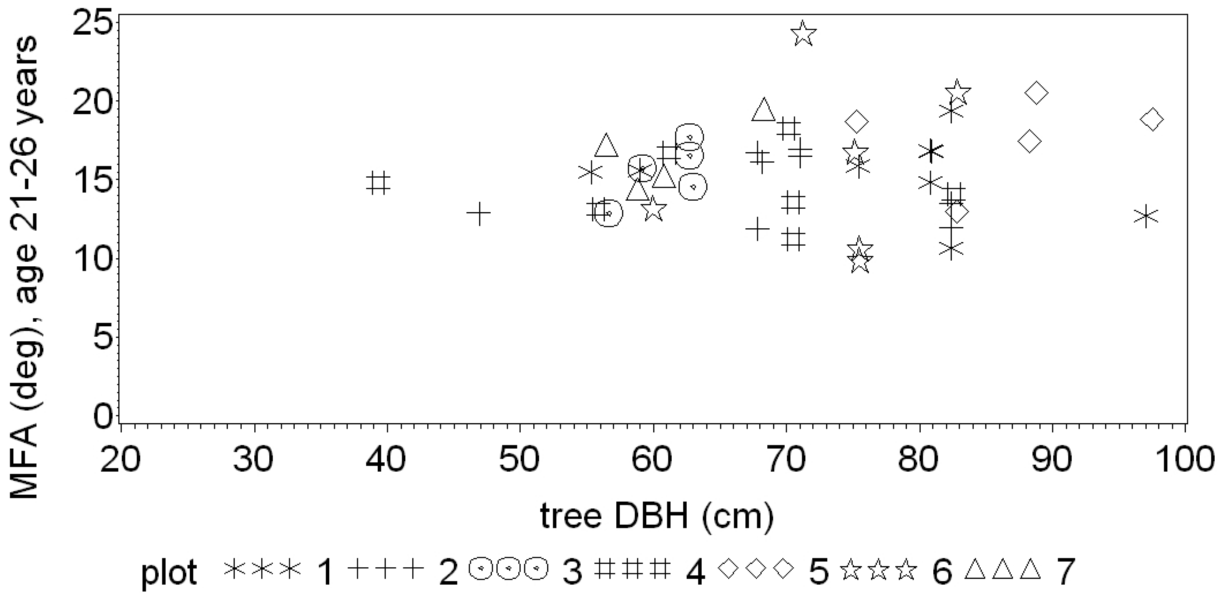

FIGURE 8: Relationship between ring-average microfibril angle for rings 21 to 26 years and DBH at age 26 years for individual trees in separate plots.

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(prior to the final thinning), all plots had the same nominal number of stems per hectare but had received different pruning treatments. At this point, mean ring-average MFA was highest in the unpruned plots (plots 5 and 7), and lowest in the plots that were severely pruned (plots 1 and 3), Table 5. After the final thinning, a downward trend in ring-average microfibril angle was observed for most of the individual trees. However, this trend was interrupted in the two plots that had received the severe pruning treatment. Between ages 7 and 10, plot mean ring-average MFA increased on average by 4.7 degrees in plot 1 (thinned to 131 stems ha^{-1}) and 0.1 degrees in plot 3 (thinned to 351 stems ha^{-1}), Table 4.

It is speculated that the high centre of gravity for plot-1 trees after pruning together with the large increase in growing space after thinning caused the substantial increase in plot mean MFA between age 7 and 10 years. Trees in plots 2 and 5 were also thinned to the same final number of stems per hectare (approximately 130 stems ha^{-1}) as those in plot 1 but plot-2 trees received a pruning treatment that kept the centre of gravity of the crowns lower, while plot-5 trees were not pruned at all, Table 2. Mean MFA values for these latter two plots decreased considerably from age 7 to 10 years, Table 4.

Similarly, plot mean MFA from age 7 to 10 years increased slightly for trees in plot 3 but not those in plot 4, Table 4. Plot 3 was pruned more severely than plot 4, however both plots were thinned less severely (to approximately 350 stems ha^{-1}) than plots 1, 2 and 5.

An increase in MFA following thinning in pruned stands has been previously noted (Grace, unpublished data). These unpublished data indicated that the increase in MFA following thinning was larger with increasing severity of the thinning.

Are these changes in MFA the result of increased tree movement following pruning and thinning? Moore and Maguire (2005) showed that removing up to 80% of the green crown mass or up to 50% of the green crown length had little effect on damping ratio or natural frequency in Douglas-fir. This suggests an immediate change in MFA is unlikely to occur as a result of pruning. Moore (pers. comm.) considered that changes in applied wind loads as a result of the thinning and pruning would be small. On the other hand, this study showed an increase in microfibril angle which was sometimes accompanied by a decrease in maximum latewood after heavy thinning and pruning. Both increased microfibril angle and decreased latewood density were observed in flexure wood by Telewski (1989) so it is possible that the observed trends are a result of increased flexure. The increase in microfibril angle is temporary. Close to the time of harvest, when the forest has a closed canopy, there were no significant differences in average microfibril angle for rings 21-26 with DBH or with silvicultural treatment.

Further research, so far without success, is underway to determine whether these individual-tree trends in microfibril angle can be predicted from tree and stand variables, in particular tree spacing and crown dimensions. It is possible that a more detailed approach is required.

Summary

The objective of the study was to determine the usefulness of final tree dimensions (tree DBH in this case) in predicting wood properties. Once tree DBH had been accounted for, density variables studied were not influenced by silvicultural treatment. However, final DBH was not sufficient to predict MFA variables around the time of, and in years immediately following, final thinning.

This study shows that pruning has a significant impact on microfibril angle and that heavy pruning together with heavy thinning result in an increase in microfibril angle for several years after treatment. To our knowledge, such an interaction between thinning and pruning treatments has not previously been documented.

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References

Ainsworth, P. (1989). Wind damage in radiata pine: The Tasman experience. In A. Somerville, S. Wakelin & L. Whitehouse (Eds.), *Workshop on wind damage in New Zealand exotic forests. FRI Bulletin No, 146* (pp. 6-9): Forest Research Institute, Ministry of Forestry.

Asner, G. P., & Goldstein, G. (1997). Correlating stem biomechanical properties of Hawaiian canopy trees with hurricane wind damage. *Biotropica, 29*(2), 145-150.

Barbour, R. J., Fayle, D. C., Chauret, G., Cook, J., Karsh, M. B., & Ran, S. (1994). Breast-height relative density and radial growth in mature jack pine (*Pinus banksiana*) for 38 years after thinning. *Canadian Journal of Forest Research, 24*(12), 2439-2447.

Cameron, A. D., & Dunham, R. A. (1999). Strength properties of wind- and snow-damaged stems of *Picea sitchensis* and *Pinus sylvestris* in comparison with undamaged trees. *Canadian Journal of Forest Research, 29*(5), 595-599.

Cown, D. J. (1973). Effects of severe thinning and pruning treatments on the intrinsic wood properties of young radiata pine. *New Zealand Journal of Forestry Science, 3*(3), 379-389.

Cown, D. J. (1974). Comparison of the effects of two thinning regimes on some wood properties of radiata pine. *New Zealand Journal of Forestry Science, 4*, 540-551.

Cregg, B. M., Dougherty, P. M. & Hennessey, T. C. (1988). Growth and wood quality of young loblolly pine trees in relation to stand density and climatic factors *Canadian Journal of Forest Research, 18*, 851-858.

Gardiner, B., Peltola, H., & Kellomäki, S. (2000). Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecological Modelling, 129*(1), 1-23.

Gartner, B. L., Robbins, J. M., & Newton, M. (2005). Effects of pruning on wood density and tracheid length in young Douglas-fir. *Wood and Fiber Science, 37*(2), 304-313.

Goulding, C. J., & Inglis, C. S. C. (1990). The use of uniform precision, response surface designs in experiments to capture growth and yield data. In R. N. James & G. L. Tarlton (Eds.), *New approaches to spacing and thinning in plantation forestry.* (FRI Bulletin 151; pp 98-105). Rotorua, New Zealand: Forest Research Institute and Ministry of Forestry.

James, R. N. (1990). Evolution of silvicultural practice towards wide spacing and heavy thinning in New Zealand. In R. N. James & G. L. Tarlton (Eds.), *New approaches to spacing and thinning in plantation forestry.* (FRI Bulletin 151; Pp 13-20). Rotorua, New Zealand: Forest Research Institute and Ministry of Forestry.

Lachenbruch, B., Moore, J. R., & Evans, R. (2011). Radial variation in wood structure and function in woody plants, and hypotheses for its occurrence. In F. C. Meinzer, B. Lachenbruch & T. E. Dawson (Eds.), *Size- and age-related changes in tree structure and function.* (pp. 121-164). Berlin Heidelberg, Germany: Springer.

Larson, P. R. (1962). A biological approach to wood quality. *Tappi, 45*, 443-448.

Larson, P. R. (1969). *Wood formation and the concept of wood quality.* (Yale University, School of Forestry Bulletin No. 74). Falls Villages, CT, USA: Yale University.

López, B. C., Sabate, S., & Gracia, C. A. (2003). Thinning effecs on carbon allocation to fine roots in a *Quercus ilex* forest. *Tree Physiology, 23*, 1271-1224.

Megraw, R. A. (1985). *Wood quality factors in Loblolly pine*. Norcross, GA: Tappi Press.

Mörling, T. (2002). Evaluation of annual ring width and ring density development following fertilisation and thinning of Scots pine. *Annals of Forest Science, 59*(1), 29-40.

Moore, J. R., & Maguire, D. A. (2005). Natural sway frequencies and damping ratios of trees: influence of crown structure. *Trees - Structure and Function, 19*, 363-373.

Myers, R. H. (1971). *Response Surface Methodology.* Boston, MA, USA: Allyn and Bacon.

Peltola, H., Kilpeläinen, A., Sauvala, K., Räisänen, T., & Ikonen, V. P. (2007). Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. *Silva Fennica, 41*(3), 489-505.

Pont, D., Brownlie, R. K., & Grace, J. C. (2007). Disc image-processing software for three-dimensional mapping of stem ring width and compression wood. *New Zealand Journal of Forestry Science, 37*(2), 169-185.

Quine, C. P., & Gardiner, B. A. (2007). Understanding how the interaction of wind and trees results in windthrow, stem breakage and canopy gap formation. In E. A. Johnson & K. Miyanishi (Eds.), *Plant disturbance ecology: the process and the response.* Academic Press.

Santantonio, D., & Santantonio, E. (1987). Effect of thinning on production and mortality of fine roots in a *Pinus radiata* plantation on a fertile site in New Zealand. *Canadian Journal of Forest Research, 17*, 919-928.

Sutton, W. R. J., & Harris, J. M. (1974). Effect of heavy thinning on wood density in radiata pine. *New Zealand Journal of Forestry Science, 4*, 112-115.

Telewski, F. W. (1989). Structure and function of flexure wood in *Abies fraseri. Tree Physiology, 5*, 113-121.

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ISSN 1179-5395 (on-line)

Urban, S. T., Lieffers, V. J., & MacDonald, S. E. (1994). Release in radial growth in the trunk and structural roots of white spruce as measured by dendrochronology. *Canadian Journal of Forest Research, 24*(8), 1550-1556.

Wilson, B. F., & Archer, R. R. (1979). Tree Design: Some biological solutions to mechanical problems. *BioScience, 29*, 293-298.

Zobel, B. J. & van Buijtenen, J. P. (1989) *Wood variation, Its causes and control.* Berlin Heidelberg, Germany: Springer-Verlag.

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