Effects of nitrogen (N) and phosphorus (P) fertilizers on average fibre radial diameter, tangential diameter, wall thickness and number of fibres per unit area were studied over 7 years of growth in radiata pine. Stands were in mid-rotation, thinned and treatments replicated 4 times at 3 sites. Compared to a thinned, unfertilized control, N decreased and P increased fibre radial diameter. Only N decreased fibre radial diameter, thereby increasing the number of fibres per unit area. All fertilizer treatments decreased fibre wall thickness. Responses in ring width and fibre properties, other than fibre tangential diameter peaked 2 years following fertiliser application, before gradually disappearing after 4–5 years. Fertilizer effects on fibre properties diminished at different rates, causing significant interactions with time. Ring width had little effect on density. Changes in density and fibre coarseness were attributed to changes in fibre wall thickness more than fibre radial diameter and tangential diameter. The largest decrease in density and fibre coarseness in the combined N and P treatment was explained mostly by thinner walls.

Key words: Pinus radiata, N and P fertilizers, fibre properties, wood quality, Australia.

INTRODUCTION

A review on the effect of thinning and fertilizer application on growth and wood properties in radiata pine (Pinus radiata D. Don) by Nyakuengama et al. (2001) indicated that applying fertilizer in mid-rotation was economically more attractive than applying it earlier because the invested dollar targets older wood of higher quality (higher density and fibre length; lower spiral grain and microfibril angle) and the investment period is shorter. The review identified key wood properties affecting the suitability of wood for timber and paper end-uses (e.g. density, earlywood:latewood ratio, stiffness, microfibril angle, spiral grain, compression wood and fibre length). The review found that:

a) Growth response to fertilizer could be large but was highly variable depending on site specific factors (e.g. available water and soil fertility);
b) In percentage terms, growth gain exceeded density reduction by a factor of five;
c) Growth gain and density reduction lasted between 3 and 7 years;
d) There was no consensus in the literature regarding the correlation between growth and density; and
e) Changes in fibre anatomical properties that underpin responses in growth and density were not widely studied on account of the high cost of measurement. Therefore, the effect of growing conditions on growth and wood properties (density) were not resolved at the fibre anatomical level.

The purpose of the present investigation is to examine the fibre anatomical changes, associated with the previously reported changes in growth and density (Nyakuengama et al. 2002), that occur in response to nitrogen (N) and phosphorus (P) fertilizer applied to radiata pine in mid-rotation. Using the same material, sample preparation, data acquisition and analysis methods, changes in fibre diameter, wall thickness, and coarseness are quantified to further explain changes in ring width and density.

MATERIALS AND METHODS

Site, silvicultural treatment and sampling information is the same as in Nyakuengama et al. (2002). Three radiata pine plantations were selected from Longford, Carabost and Mount Gambier in Australia. Measurable growth responses to fertilizer were evident (minimum of 6 m³ ha⁻¹ in 7 years) and at least 7 years of post-treatment growth were available.

The Longford plantation (experiment number VRK142) is owned by Australian Paper Plantations and located in southeast Gippsland, Victoria (38° 16' S, 146° 40' E). Its average annual rainfall is 610 mm and the soil type is duplex (Sd, Dy 5.21/Dy 3.41, Northcote, 1984) derived from the Flynn and Gormandale Sands. The Carabost plantation (experiment number N10141) is owned by New South Wales State Forests. The site is located 23 km northwest of Tumbarumba, New South Wales (147° 48' E, 35° 39' S). The average annual rainfall is 934 mm and the soil is a lithosol (Uf 1.43, Northcote, 1984) derived from Ordovician shales. The Mount Gambier plantation (experiment number EM99) is owned by Auspine Limited and is located near Mount Gambier, South Australia (137° 30' S, 140° 48' E). The average annual rainfall is 694 mm and the soil type is yellow podzol or soloth (DY 5.32, Northcote, 1984).

Silvicultural history

Four contrasting fertilizer treatments were applied following thinning at each site (control, N, P and NP). The Longford plantation was established in 1972 and thinned prior to fertilizer application in 1986 (age 14). The control, P, N and NP treatments were sampled at age 26. Fertilizer application rates were nil and 100 kg ha⁻¹ P and 200 kg ha⁻¹ N (i.e. N₀P₀, N₀P₁₀₀, N₂₀₀P₀ and N₂₀₀P₁₀₀, respectively) (Pongracic et al. 1995). The Carabost plantation was established in 1965 and thinned immediately prior to fertilizer application in 1982 (age 17). The control, P, N and NP treatments were sampled at age
32. Fertilizer application rates were nil and 225 kg ha\(^{-1}\) (i.e. N\(_0\)P\(_0\), N\(_0\)P\(_{225}\), N\(_{225}\)P\(_0\) and N\(_{225}\)P\(_{225}\), respectively (Carter 1985). The Mount Gambier plantation was established in 1977, thinned in 1988 (age 10) and fertilized 11 months later. Control, P, N, NP and 2NP treatments sampled at age 21. Fertilizer application rates were nil and 200 kg ha\(^{-1}\) N and 80 kg ha\(^{-1}\) P (i.e. N\(_0\)P\(_0\), N\(_0\)P\(_{80}\), N\(_{200}\)P\(_0\), N\(_{200}\)P\(_{80}\) and N\(_{400}\)P\(_{80}\), respectively (Carlyle 1998). Only the N\(_{200}\)P\(_{80}\) treatment was used in this study.

**Sampling**

At each site, ten dominant/co-dominant trees were sampled in each of four replicates of each treatment (3 sites × 4 treatments (including control) × 4 replicates × 10 trees = 480 trees) by removing a 12-mm diameter increment core near breast-height (1.1 m). Owing to financial constraints, only twenty air-dried cores of each treatment at each site were randomly selected and prepared for SilviScan analysis (Evans 1994; Evans et al. 1995). Ring width, density, fibre radial diameter, fibre tangential diameter, fibre wall thickness and fibre numerical density (fibres per unit cross-sectional area), were measured using SilviScan. Of these ring width, density, fibre radial diameter and fibre tangential diameter are direct and independent measurements. Fibre wall thickness, coarseness and fibre numerical density are derived from them. All changes in fibre anatomy due to fertilizer were compared to a thinned, unfertilized control.

Responses were examined two ways. Firstly, average treatment responses were obtained by averaging across annual rings formed during the seven years after fertilizer application (post-treatment). An analysis of variance (ANOVA) was used to study the effect of site and fertilizer treatment on the properties of all wood formed seven years following treatment (Genstat 5 Committee 1997). Secondly, annual responses were determined in individual growth rings formed during the post-treatment period. In both cases, results were corrected for pre-existing differences between trees using data from the five years before treatment as a covariate (trait covariates). Growth response to thinning and fertilizer is conventionally assessed within seven years following treatment in radiata pine. Here too, fertilizer responses in wood properties were assessed in the seven years following treatment. Each wood property was measured in consecutive growth rings in every tree in order to study the effect of site and fertilizer treatment on wood formed in the individual seven years following treatment. Therefore, the measurements were autocorrelated over time and in space. To take account of the autocorrelation a first order regressive autocorrelation (AR1) correction was applied to the random error term using the time series analysis. Parameters were estimated using the REsidual Maximum Likelihood (REML) (Genstat 5 Committee 1997; Wood 1999). Treatment, tree age and trait covariates were specified as the fixed effects, and sites, replicates and trees were modelled as random effects. In order to test for significance of fixed effects, Wald statistics were compared with Chi-squared at the 95% confidence level with the degrees of freedom of the fixed effects (Genstat 5 Committee 1997; Gooding et al. 1997).

Relationships between ring width, density and fibre properties were studied using Pearson product moment coefficients and the significance tested following Snedecor (1950).
RESULTS

Seven year post-treatment period

Average responses

The fibre properties existing prior to treatment explained a significant proportion of the variances in the data, as did the trees’ age at the time the treatments were applied. Accounting for these differences allowed treatment effects to be more clearly defined. ANOVA results indicated highly significant differences between sites in all fibre properties (Table 1). Apart from fibre radial diameter, fibre properties were similar at Longford and Carabost (Table 2). Trees from Mount Gambier had the lowest fibre numerical density, the largest fibre tangential diameter and the highest fibre wall thickness and fibre coarseness.

Wald statistics from the REML analysis (Table 3) revealed that treatment, time since treatment, the interaction between time since treatment and treatment, trait covariates measured 5 years prior to treatment, and tree age, were the main sources of variation in responses in all properties, except fibre tangential diameter. The latter was not influenced by silvicultural treatment or tree age.

Compared with the control, only N increased fibre numerical density (Table 4). Fibres per unit area were fewer than the control in the other treatments, especially P. Only N

<table>
<thead>
<tr>
<th>Fibre property</th>
<th>Variable</th>
<th>Degrees of freedom</th>
<th>Mean sum of squares</th>
<th>F ratio</th>
<th>F probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibres per unit cross-sectional area</td>
<td>Site</td>
<td>2</td>
<td>170718</td>
<td>17.39</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – fibres per area</td>
<td>1</td>
<td>9107263</td>
<td>925.51</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – tree age</td>
<td>1</td>
<td>1156234</td>
<td>117.50</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1675</td>
<td>9840</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial diameter</td>
<td>Site</td>
<td>2</td>
<td>19.266</td>
<td>4.65</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Covariate – radial diameter</td>
<td>1</td>
<td>4035.674</td>
<td>973.69</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – tree age</td>
<td>1</td>
<td>432.669</td>
<td>104.39</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1675</td>
<td>4.145</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tangential diameter</td>
<td>Site</td>
<td>2</td>
<td>38.260</td>
<td>20.95</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – tangential diameter</td>
<td>1</td>
<td>1560.161</td>
<td>854.15</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – tree age</td>
<td>1</td>
<td>100.206</td>
<td>54.86</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1675</td>
<td>1.827</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall thickness</td>
<td>Site</td>
<td>2</td>
<td>19.29667</td>
<td>247.48</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – wall thickness</td>
<td>1</td>
<td>59.75661</td>
<td>766.39</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – tree age</td>
<td>1</td>
<td>12.85069</td>
<td>164.81</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1675</td>
<td>0.07797</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarseness</td>
<td>Site</td>
<td>2</td>
<td>503858</td>
<td>213.36</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – coarseness</td>
<td>1</td>
<td>2023085</td>
<td>856.69</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Covariate – tree age</td>
<td>1</td>
<td>584491</td>
<td>247.51</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>1675</td>
<td>2362</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
decreased fibre radial diameter, whereas P had the largest positive effect. Little change in fibre tangential diameter was evident, with the NP treatment producing the smallest fibre tangential diameter. All treatments significantly reduced fibre wall thickness, NP having the greatest effect. Apart from P, the treatments significantly reduced fibre coarseness.

Table 2. Means of fibre properties at three sites over the 7-year post-treatment period. Numbers with the same letters in the same column are not significantly different (p < 0.05).

<table>
<thead>
<tr>
<th>Site</th>
<th>Fibre number per area (mm²⁻²)</th>
<th>Radial diameter (µm)</th>
<th>Tangential diameter (µm)</th>
<th>Wall thickness (µm)</th>
<th>Coarseness (µg m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longford</td>
<td>1076 a</td>
<td>32.68 a</td>
<td>29.00 b</td>
<td>3.02 b</td>
<td>491 b</td>
</tr>
<tr>
<td>Carabost</td>
<td>1086 a</td>
<td>32.35 b</td>
<td>28.85 b</td>
<td>3.00 b</td>
<td>484 b</td>
</tr>
<tr>
<td>Mount Gambier</td>
<td>1030 b</td>
<td>32.86 a</td>
<td>29.65 a</td>
<td>3.54 a</td>
<td>572 a</td>
</tr>
</tbody>
</table>

Table 3. The Wald statistics from the REML analysis for fibre properties are shown. Asterisks indicate the level of significance.

<table>
<thead>
<tr>
<th>Fibre property</th>
<th>Treatment (d.f. = 3)</th>
<th>Time (d.f. = 6)</th>
<th>Treatment × Time (d.f. = 18)</th>
<th>Trait covariate (d.f. = 1)</th>
<th>Tree age (d.f. = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre number per area</td>
<td>32**</td>
<td>243**</td>
<td>30*</td>
<td>321**</td>
<td>6*</td>
</tr>
<tr>
<td>Radial diameter</td>
<td>64**</td>
<td>433**</td>
<td>35**</td>
<td>406**</td>
<td>27**</td>
</tr>
<tr>
<td>Tangential diameter</td>
<td>6</td>
<td>132**</td>
<td>60**</td>
<td>255**</td>
<td>0</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>47**</td>
<td>788**</td>
<td>137**</td>
<td>269**</td>
<td>148**</td>
</tr>
<tr>
<td>Coarseness</td>
<td>15**</td>
<td>493**</td>
<td>91**</td>
<td>294**</td>
<td>56**</td>
</tr>
</tbody>
</table>

** = significant at 1%; * = significant at 5%; d.f. = degrees of freedom.

Table 4. Effect of fertilizer on fibre properties. Numbers with the same letters in the same column are not significantly different (p < 0.05). Percentage change relative to the control are indicated.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fibres per unit area</th>
<th>Radial diameter</th>
<th>Tangential diameter</th>
<th>Wall thickness</th>
<th>Coarseness</th>
<th>Fibres per unit area</th>
<th>Radial diameter</th>
<th>Tangential diameter</th>
<th>Wall thickness</th>
<th>Coarseness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1069 ab</td>
<td>32.35 b</td>
<td>29.30 ab</td>
<td>3.28 a</td>
<td>526 a</td>
<td>3.21 b</td>
<td>-1</td>
<td>29.01 b</td>
<td>negligible</td>
<td>511 b</td>
</tr>
<tr>
<td>N</td>
<td>1093 a 2</td>
<td>32.02 b</td>
<td>29.01 b</td>
<td>negligible</td>
<td>522 ab</td>
<td>3.18 b</td>
<td>-3</td>
<td>29.39 a</td>
<td>negligible</td>
<td>522 ab</td>
</tr>
<tr>
<td>P</td>
<td>1034 c -3</td>
<td>33.22 a</td>
<td>28.95 b</td>
<td>-1</td>
<td>503 c -4</td>
<td>3.09 c</td>
<td>-6</td>
<td>28.95 b</td>
<td>-1</td>
<td>503 c -4</td>
</tr>
<tr>
<td>NP</td>
<td>1060 bc -1</td>
<td>32.93 a</td>
<td>28.95 b</td>
<td>-1</td>
<td>503 c -4</td>
<td>3.09 c</td>
<td>-6</td>
<td>28.95 b</td>
<td>-1</td>
<td>503 c -4</td>
</tr>
</tbody>
</table>
Annual responses

In the first two years of the 7-year post-treatment period ring width (i.e. growth rate) increased to a maximum (Nyakuengama et al. 2002). During this period, fibre numerical density and fibre wall thickness declined rapidly and fibre radial diameter increased sharply (Fig. 1). In subsequent years ring width response declined and fibre properties changed slowly (increased or decreased) at rates dependent on treatments. Compared to the control, the treatment effect lasted for 4–5 years in all fibre properties except fibre tangential diameter. Response was localised for a couple of years and nil overall in fibre tangential diameter.

Radial profiles of ring width were similar in all treatments and responses were similar in N and P fertilizer treatments during the 7-year post-treatment period (Nyakuengama et al. 2002). Growth response was positive in all treatments and strongest in the NP treatment. Overall, the effect of fertilizer on fibre numerical density was significant.
during the first 5 years (Fig. 1a). Fibre numerical density was initially high but declined with time in all treatments. Phosphorus and control treatments had highest fibre numerical density at the start of the experiment. The rate of fibre numerical density decline differed between treatments in the initial two years, being lowest in the NP treatment. In general, fibre numerical density was highest and lowest in the N and P treatment, respectively. Significant interactions between treatment and time were mainly between the control and NP treatments.

Fibre radial diameters were significantly different between treatments between the second and sixth years after treatment (Fig. 1b). After being similar between treatments in the first year, fibre radial diameter increased curvi-linearly with time. However, the increase was most rapid in the P and NP treatments and fibre radial diameter decreased in the N treatment relative to the control. Overall, fibre radial diameter was significantly larger in the P and NP treatments than in N and control treatments. Interactions between treatment and time were due to inconsistent responses in different treatments.

Time profiles of fibre tangential diameter were similar between control and P and between N and NP treatments (Fig. 1c). Fibre tangential diameter was largest in control and P treatments and smallest in the NP treatment. Of note, fibre tangential diameter increased quasi-linearly with time since treatment only in the control and P treatments. Significant responses were restricted to between the third and sixth years following treatment.

The effect of fertilizer on fibre wall thickness lasted for 4 years following treatment (Fig. 1d). Fibre wall thickness decreased to a minimum in 2–3 years, then increased. The results suggest that fibre wall thickness changed least in the control and the most in the NP treatment. The rate of change with time in fibre wall thickness was similar in the N and NP treatments, albeit minimum fibre wall thickness was lower in the latter. Fibre wall thickness remained the same from the second to the fourth year and from the fifth to the sixth year only in the P treatment. Relative to the control, fibre wall thickness increased with time at a faster rate in N and NP treatments. Collectively, the different time-related changes in fibre wall thickness between treatments underpinned significant interactions between treatment and time (Table 3).

The time profile of fibre coarseness (Fig. 1e) resembles those of fibre wall thickness and fibre tangential diameter (Fig. 1c, d) due to moderately strong correlations with the two fibre cross-sectional dimensions (see Table 6). The effect of fertilizer on fibre coarseness lasted for 4 years. Significant treatment by time since treatment interactions were mainly due to NP and N having different responses over time to the other two treatments.

Radial variability

The coefficient of variation in any fibre property during the post treatment period (Table 5) exceeded the difference between peak responses across treatments (Fig. 1). Ring width and fibre tangential diameter exhibited the most and least variability, respectively. Radial variation in fibre radial diameter was slightly less than density. Variances in fibre wall thickness and fibre coarseness were similar because the fibre properties were both mathematically derived from fibre diameter and density (Evans...
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et al. 1995). Fertilizer treatment had a significant effect on variability in all wood properties, except fibre radial diameter. Except in fibre radial diameter, variability in wood properties decreased in the order NP, N, P and control. Fibre numerical density was not a direct measurement but was calculated from cell dimensions, hence radial variability is explained by the variance of these parameters. The technological significance of variation in wood properties is discussed below.

Pearson correlations between fibre properties, ring width and density

The interrelationships between fibre properties, ring width and density were investigated across the post treatment period in the three sites. Results suggest that ring width was weakly, negatively correlated with density, and positively with fibre radial diameter (Table 6). Density was weakly, inversely correlated with fibre radial and tangential diameters which, in turn, were weakly, positively correlated.

<table>
<thead>
<tr>
<th>Wood property</th>
<th>Control</th>
<th>P</th>
<th>N</th>
<th>NP</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring width (mm)</td>
<td>28.66 c</td>
<td>34.42 b</td>
<td>35.99 b</td>
<td>42.46 a</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Density (kg m⁻³)</td>
<td>6.27 c</td>
<td>6.76 bc</td>
<td>7.26 b</td>
<td>8.63 a</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Fibre radial diameter (µm)</td>
<td>4.89 a</td>
<td>5.08 a</td>
<td>4.80 a</td>
<td>5.11 a</td>
<td>0.775</td>
</tr>
<tr>
<td>Fibre tangential diameter (µm)</td>
<td>2.87 b</td>
<td>3.22 b</td>
<td>3.50 a</td>
<td>3.77 a</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Fibre wall thickness (µm)</td>
<td>6.59 b</td>
<td>6.83 b</td>
<td>7.68 b</td>
<td>9.53 a</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Fibre coarseness (µm m⁻¹)</td>
<td>6.78 b</td>
<td>6.94 b</td>
<td>8.06 b</td>
<td>9.67 a</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Table 5. Coefficient of variation (%) in growth and wood properties. Numbers with the same letters in the same row are not significantly different (p < 0.05).

| Ring width                      | 1       |       |
| Density                        | -0.36   | 1     |
| Fibre radial diameter          | 0.32    | -0.42 | 1     |
| Fibre tangential diameter      | -0.08   | -0.14 | 0.39  | 1     |

Table 6. Pearson correlation coefficients for ring width, density, fibre radial diameter and fibre tangential diameter. All data from the three sites were analysed (n = 1680). Bold values are significant at p < 0.01.

DISCUSSION

Overview

Systematic differences were evident in wood density seven years following N, P and NP fertilizer treatments. For example, the control (587 kg m⁻³) and N treatment (579 kg m⁻³) had similar wood densities (Nyakuengama et al. 2002). The P treatment (564 kg m⁻³) and NP treatment (555 kg m⁻³) had similar but significantly lower wood
densities than either the control or N treatments (Nyakuengama et al. 2002). Similarly, there were significant differences in fibre properties due to fertilizer application. In comparison to the control, N fertilizer increased fibre numerical density, decreased fibre radial diameter and fibre wall thickness, P fertilizer increased fibre radial diameter and decreased fibre wall thickness, and NP fertilizer decreased fibre wall thickness and increased fibre radial diameter. Fibre properties were significantly different between sites, with one of the three sites (Mount Gambier) producing larger fibres (fibre radial and tangential diameters) with higher fibre wall thickness and fibre coarseness. The highly significant effects of covariates demonstrated the utility of correcting treatment responses for pre-existing differences between treatments and tree age. Consequently, covariate analysis is recommended in similar studies. The need to correct for autocorrelation between variables measured in consecutive growth rings was discussed previously (Nyakuengama et al. 2002).

**Cellular responses**

**Cell division**

Fertilizing with N increased fibre numerical density (Table 4, Fig. 1). The increased cambial cell production in N fertilized trees is due to an increased cell division rate and not to an extension of the cell production period (Brix & Mitchell 1980). The literature suggests that stem radius increases as a function of increased rates of cell production in thinned, N fertilized trees (Hagner 1969; Brix & Mitchell 1980). It is uncertain if nitrogen affects the number of dividing cambial cells or the rates of individual cell division. Generic studies suggest that P is important for cell division and structure (Mustanoja & Leaf 1965).

**Fibre size**

Fibre radial diameter responses were small in this study and within the range (2–9%) found in thinned or fertilized conifers (Smith 1968; Siddiqui et al. 1971; Cown 1972). Responses were generally larger in fibre radial diameter than fibre tangential diameter in this study on radiata pine. Similar trends were observed in loblolly pine (*Pinus taeda* L.) (Posey 1964) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Erickson & Harrison 1974). It appears that fibre radial diameter is more responsive to environmental variables than fibre tangential diameter. Indeed, Nyakuengama (1997) found this to be the case in radiata pine in relation to rainfall and temperature.

Nitrogen decreased fibre diameter in this study. However, it had little effect on Douglas-fir (Brix & Mitchell 1980). Phosphorus increased fibre radial diameter in this study as was the case in loblolly pine (Posey 1964). It is unclear if phosphorus fertilizer changes growth phenology (i.e. proportion of early to late season growth) or if it causes a real increase in fibre size. Nonetheless, P lowered density compared to the control treatment in radiata pines (Nyakuengama et al. 2002) and in loblolly pine (Posey 1964). This is because of the inverse relationship between fibre size and density. Nitrogen and phosphorus when applied together slightly increased fibre radial diameter in this study but apparently had no effect in other studies (Posey 1964; Sastry & Wellwood 1971).
Fibre wall thickness

Fertilizer has differing effects on fibre wall thickness. Nitrogen had little effect on fibre wall thickness in this study as in other N and NP fertilizer studies (Williams & Hamilton 1961; Youngberg et al. 1963). These fertilizers reduced fibre wall thickness in other studies (Orman & Harris 1963; Santos et al. 1967; Siddiqui et al. 1971). Some studies found a decrease of between 6–14% following P or NP fertilizer application (Williams & Hamilton 1961; Posey 1964) and yet others an increase of around 12% following K fertilizer application (Gray & Kyanka 1974).

Interrelationship between ring width, fibre properties and density

Pearson correlation coefficients of ring width and wood properties suggest significant, but weak interrelationships (Table 6). This finding agrees with previous generic studies in this species (Evans et al. 1995; Nyakuengama 1997). This means that there was no direct correspondence between growth gain and changes in wood properties due to fertilizer application. Correlations reported in this study were obtained across growth rings formed during the seven year following treatment. Therefore, the effect of tree age was confounded (Turnbull 1949; Larson 1969).

Implications for end products

Percentage changes were small in fibre properties (radial and tangential diameters, wall thickness and numerical density) and comparable to decreases in density and fibre coarseness during the 7-year post treatment period. The changes in fibre anatomy were several orders of magnitude smaller than increases in ring width. This conclusion is somewhat similar to that found previously: that growth gain exceeded density reductions in thinned or fertilized coniferous stands (Paul 1957; McKinnell & Rudman 1973; Hunt et al. 1980; Cown & McConchie 1981; Zobel & Van Buijtenen 1989; Fife et al. 1993). This makes later-age fertilizer application economically attractive since large gains from production of greater volumes offset the small reductions in density (and presumably timber strength). Growers and processors will need to make informed decisions considering the trade-off between growth gains and density reductions for particular site, silviculture, genotype and targeted end-use products.

The time course studies suggested the effect of fertilizer on ring width and most wood properties lasted for 4–5 years. Thereafter, wood properties reverted to levels similar to or higher than those before treatment on account of being physiologically older. The economic implication of the result is that a second fertilizer application preceded by a thinning to stimulate growth would be possible at the end of 4–5 years. More importantly, the second fertilizer application is unlikely to adversely affect wood properties.

Density is a strong direct predictor of timber strength (Cown et al. 1999). Therefore, timber strength relevant to technological applications is expected to decrease in the order control, N, P and NP. It is difficult to estimate the percentage decrease in the timber strength on the basis of density alone. Other important factors affecting timber strength (e.g. microfibril angle and knot size) were not the object of this study and
therefore their impact on timber strength cannot be estimated. However, it is expected
that reductions in timber strength would be relatively small since the largest density
difference (30 kg m\(^{-3}\)) was between the control and NP treatments. Further, a reduction
of 50 kg m\(^{-3}\) in density would cause a detectable reduction in strength in radiata pine
(McKinnell 1970).

The control and P treatments had similar fibre coarseness, albeit for different reasons.
Fibres were much larger in fibre radial diameter but with thinner fibre walls in the
P treatment. The NP treatment had significantly lower fibre coarseness than the control
because of much thinner fibre walls. Collectively, the results imply that pulp fibres from
the P and NP treatments would be more pliable but weaker than the control. Pulp prop-
erties would be expected to be similar between the control and N treatments because
fibre properties were most similar. In general, increased anticlinal cell division rate
leads to shorter fibres (Bannan 1954, 1967) so it can be hypothesised that pulp from
N fertilized trees could have shorter fibres. However, it not possible to predict precise
fibre behaviour during refining without a pulping trial.

Peak fertilizer responses in fibre properties were smaller than the radial variations
across growth rings formed during the post treatment period. The NP fertilizer treatment
resulted in the largest growth response, largest decrease in density and fibre coarse-
ness but the greatest variability in all wood properties. It is technologically desirable
to minimise within-tree variation in wood properties. Therefore, it is hypothesized that
within-tree variability in wood properties would be lowest and highest in the control
and NP treatments, respectively.

CONCLUSIONS

The importance of including fibre properties in wood quality studies of fertilized stands
has been demonstrated by this study. For example, although N and P had a comparable
ring width response, they decreased and increased fibre radial diameter, respectively.
Further, fibre wall thickness was lower in N than P in the initial 3 years but the reverse
was true in the rest of the study, accounting for the similar average fibre wall thickness
between N and P treatments. The differing responses of fibres to N and P accounted for
the impact of these fertilizers on wood properties and ultimately wood quality.

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