NEW ZEALAND DOUGLAS FIR TIMBER QUALITY IN RELATION TO SILVICULTURE

I. D. Whiteside, M. D. Wilcox and J. R. Tustin*

Abstract

The results of a number of recent timber and wood quality studies on New Zealand-grown Douglas fir have some important silvicultural implications. Branch size is by far the most important factor influencing timber stiffness and strength, and density is the next most important. In a recent study they together accounted for about 80% of the variation that occurred in timber stiffness as revealed by machine stress-grading. The most satisfactory multiple regression equation linking modulus of elasticity of 100 × 50 mm timber loaded as a plank (E_p) with branch size and wood density was E_p (gigapascals) = 2.9014 – 0.07048 branch index (mm) + 0.01269 density (kg/m³) where E_p is the mean E_p of all pieces cut from a log, density is the mean density of these pieces, and branch index is that of the log concerned. Branch index was determined by measuring the largest branch per quartile per 1.2 m length, and averaging the 16 measurements per log so obtained.

Contrary to earlier indications, radial growth rate in itself has been shown to have only a small effect on density in wood of the same cambial age, particularly in wood more than 12 growth rings from the pith.

With machine stress-grading, much larger knot sizes can be tolerated than with visual grading to current rules, particularly when wood density is high. It is concluded that only if the sawn output is machine graded can further planting of Douglas fir for production of timber for engineering and framing uses possibly be justified.

It is considered that the objective in management of Douglas fir in New Zealand should be to grow trees as rapidly as possible and on as short a rotation as possible consistent with keeping branch index in the bottom two 4.8 m log lengths down to 36 mm, assuming that mean wood density will be approximately 400 kg/m³. If this is achieved, at least 60% of the sawn timber volume produced from the bottom two logs should qualify for exacting engineering uses with machine stress-grading. This is far superior to what can be achieved with radiata pine grown on current silvicultural schedules.

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DOUGLAS FIR TIMBER QUALITY

A silvicultural regime which should maintain branch size in the bottom two logs within the required limits is given. It involves a relatively wide initial spacing, heavy early thinning, and a short rotation age, and is radically different from regimes currently practised. No attempt is made to provide an economic justification for this regime.

INTRODUCTION

A notable feature of the timber industry in recent years has been the rapid increase in the utilisation of New Zealand-grown Douglas fir for sawn timber, to the point where it now accounts for 9% of total timber production. This increased utilisation has been accompanied by a corresponding rapid increase in export sales, with Australia the main market.

The main demand for Douglas fir sawn timber is for framing and engineering uses, and so most production is in framing sizes. About two-thirds of framing production is in 75 mm and 100 mm widths, with the remainder in wider pieces. These figures indicate that on both local and export markets the main uses are as house framing members and roof truss components.

Although much less important than radiata pine, Douglas fir is currently the number two exotic species in New Zealand. A total of 47 000 ha has been established to date, mostly in State forests since the 1920s. Much of the resource, particularly that which is ready for utilisation, is concentrated within Kaingaroa Forest in the central North Island.

The history of the establishment of Douglas fir in Kaingaroa Forest has been described by Kirkland (1969). Planting of Douglas fir at Kaingaroa commenced in 1915 and continued until 1936. From 1915 to 1922 planting was at $1.8 \times 1.8$ m spacing, but from 1923 onwards planting was at $2.4 \times 2.4$ m spacing. Establishment was of a very high standard from 1915 to 1923 with blanking being carried out meticulously. This initial care is still evident in unthinned stands, as stocking is uniformly high. From 1924 onwards the standard of establishment deteriorated sharply with the result than in unthinned stands stocking is now very variable.

In well-stocked stands the canopy is usually complete by top height 8 m, and lack of mortality, when combined with good establishment, leads to rapid suppression and death of the lower branches. Except on "wolf" trees, or on open-grown trees in canopy gaps, branch size is usually less than 40 mm, and commonly 25 mm or less. In unthinned stands the base of the green crown is 15 to 18 m above ground level by top height 27 m (age 33 years approx.).
First thinning at Kaingaroa was generally delayed until age 35 to 40 years, when the stands were heavily thinned for saw-log and pulpwood production. Generally the thinning removed the smaller trees in the stands. This silviculture resulted in the production of sawn timber well suited to end-use as framing, as branch size had been suppressed on the boles of both thinnings and final crop trees for about 15 m.

**REVIEW OF FOREST SERVICE STUDIES ON TIMBER QUALITY OF NEW ZEALAND DOUGLAS FIR**

*Studies on Wood Density in Clearwood*

The importance of wood density as an index of wood quality in softwood species has long been recognised. This is because of the close relationship that exists between density and clear timber stiffness and strength. Douglas fir timber is used primarily for framing and engineering purposes where stiffness and strength are particularly important, and therefore wood density assumes special significance in this species.

For many years it has been generally believed that in Douglas fir a strong negative correlation exists between radial growth rate and wood density, and that slow diameter increment rates must be maintained in order to produce acceptable density. Indeed, this view is widely held about conifers in general. Elliott (1970) points out that the view receives support from the interpretation of gross correlation analysis in many studies concerned with whole cross-sections or radial strips from pith to bark, which unfortunately have ignored the characteristic and systematic variation of ring width with increasing age from the pith. Thus the effects of ring width and age have been confounded. Maximum wood density values normally occur well away from the pith or log centre where, quite independently, ring width is small. Thus a gross correlation coefficient is of little value in determining the effect of ring width *per se*. Elliott states that evidence from studies which analyse the independent effect of ring width and age on basic density unequivocally indicates that ring width accounts for only a small part of the variation of basic density along the horizontal section.

The earliest and still the main authoritative reference on Douglas fir wood quality in New Zealand is “The Physical and Mechanical Properties of New Zealand-grown Douglas Fir” by Harris and Orman (1958). This paper provides data on Douglas fir clearwood from a number of localities in New Zealand. In the paper Harris and Orman recommended that an average basic specific density of 420 kg/m³ should be arrived at in growing Douglas fir in New Zealand, and that in order to
achieve this wood density a rate of growth corresponding to a ring width of 3.18 mm at breast height from the age of 15 was required. They recommended that this be the aim of silvicultural treatment. They also recommended that grading rules for structural timber should exclude pieces with less than two rings per centimetre. Correlations were estimated linking growth rate with wood density on the one hand, and wood density with clear timber strength on the other. The findings and recommendations in this paper have strongly influenced Douglas fir silviculture to the present day.

Harris (1966) described a survey of the wood density of 34- to 40-year-old stands of Douglas fir growing on 19 sites throughout New Zealand. Most stands were unthinned. He found that wood density varied widely between trees within each site, and also between sites. Rate of radial increment was the only growth factor which was found to be strongly related to wood density, accounting for about one-third of the total variation. The regression obtained between basic density of the outer wood (10 rings) at breast height and rate of growth was as follows:

\[
\text{Basic density (kg/m}^3\text{)} = 551 - 26.4 \times \text{ring width (mm)}.
\]

In the same paper Harris provided a correlation between tree average density and the density of the outerwood at breast height as follows:

\[
\text{Mean density (kg/m}^3\text{)} = 0.588 \times \text{outerwood density} + 140.
\]

The application of these formulae indicates that a radial growth rate corresponding to a ring width of 2.8 mm is required to achieve a mean tree basic density of 420 kg/m\(^3\). This agrees closely with the Harris and Orman conclusion reached in 1958.

The research results to this point appear to support the common view that a slow diameter growth rate is necessary to maintain wood density at an acceptable level. However, the results need careful interpretation. In the 1966 Harris study, a correlation coefficient of \(-0.57\) between growth rate and outerwood density was obtained by pooling results obtained over 19 sites. The within-site relationships tended to be a great deal weaker. No attempt was made to test for heterogeneity of within-site correlations or to arrive at an average within-site correlation. Neither study was directed precisely at the question of whether, within a site, radial growth rate as influenced by silviculture affects wood density, and if so to what extent. There were probably effects of genotype, site, stand age, and even sampling procedures which make the results
misleading if they are used to predict the effects of silviculture on growth rate-density relationships within a single stand.

Cown (1971) reported that, within a 45-year-old Kaingaroa stand with extreme variability in stocking and in individual tree growth rates, the association between outerwood density and growth rate at breast height was generally very weak and could be positive or negative. Vincent and Birt (1971) examined wood density in three thinned Kaingaroa stands of 46 to 47 years of age. Like Cown they found that, although there was wide variation in wood density between individual trees, the correlation in each stand between diameter growth rate and density at breast height of the outer 30 growth rings was very weak and could be positive or negative. Only over the five inner growth rings, or approximately 7 to 12 years from the pith, was there a relatively strong negative correlation, although even here growth rate accounted for only 13 to 24% of the total within-site variation in wood density.

Birt (1972), in a survey of wood density in four seed production areas at Kaingaroa, showed that in each case the mean outerwood density (10 growth rings) of the trees in the heavily thinned seed stands was greater than the mean density of the trees measured in the surrounding unthinned area. The stands varied from 19 to 48 years of age and had been thinned at least 8 years earlier.

Wilcox (1974a) examined wood density in a large number of 13-year-old provenances of Douglas fir planted in a number of locations throughout New Zealand. He found that the correlation between stem diameter and mean wood density at breast height was $-0.36$. This correlation is based on a total of 1350 trees consisting of the best 15 provenances planted on six different sites. The correlation is a pooled estimate of the within-plot correlation, which means that the effects of provenance and site have been removed. The correlation coefficient means that rate of diameter growth explains 13% of the variation in mean wood density.

In the writers' view, the results from the various studies fairly conclusively demonstrate the following:

(1) When correlations between radial growth rate and wood density are established by pooling results from stands of different provenances and ages, and/or grown on different sites, they must be interpreted with considerable caution, and almost certainly cannot be applied to individual stands.

(2) Within a single stand, radial growth rate has very little effect on wood density in wood of the same cambial age more than about 12 growth rings from the pith. Thus an
increase in radial growth rate caused by thinning will have little effect on the density of such wood. The weak correlation between growth rate and density can be either positive or negative.

(3) Within a single stand, rate of radial growth in wood in about the first 12 growth rings from the pith is negatively correlated with wood density. However, even in this zone less than 25% of the variation in wood density is associated with growth rate, and probably considerably less.

Stress Grading Studies on Sawn Timber Quality

Until recent years there has been a serious lack of technical information on mechanical properties of Douglas fir timber containing defects. The timber design section of the New Zealand Standard Model Building Bylaw NZS 1900 Chapter 9.1 (Standards Association of New Zealand, 1964) contains allowable working stresses for select and standard grades of New Zealand-grown Douglas fir from the central North Island, but how the stresses were derived remains shrouded in mystery. No grading rules were provided to enable the select and standard to be discriminated, and no data were available on timber containing defects to enable grading rules to be formulated.

The upsurge in Douglas fir utilisation commencing in the late 1960s was the stimulus to an increased research effort to obtain more knowledge on the mechanical properties of sawn timber, stiffness and bending strength in particular as it is these properties which are significant in framing and engineering uses. It was considered that more knowledge was required about the properties of clearwood, and that the effects of knots, grain deviation, and other defects on these properties should be thoroughly examined.

In 1969 an extensive programme of research on Douglas fir sawn timber was initiated using an Australian microstress stress-grading machine as the principal research tool. The major effort was concentrated on Douglas fir from Kaingaroa Forest as about 80% of timber production is from this forest. The machine stress-grading studies were accompanied by laboratory evaluation of clearwood properties and of properties of full-sized members containing defects.

The data obtained have been used to prepare standard grading rules for framing and engineering grades in Douglas fir sawn timber which will be published shortly, and to provide strength properties for these grades in the current (1976) revision of Chapter 9.1 NZS 1900. This revision will be designated NZS 3603.
The basis of operation of the microstress machine, and indeed virtually all other stress-grading machines that have been produced, is that there is a close correlation between the modulus of elasticity of timber measured as a plank \((E_p)\) and its modulus of rupture \((R)\) and modulus of elasticity measured as a joist \((E_j)\); \(E\) is the index of the stiffness of timber or the amount it will deflect when subjected to a load, and \(R\) is the index of its strength when loaded as a beam — i.e., its ability to sustain a load without breaking. The method makes use of the \(E_p-R\) and \(E_p-E_j\) correlations to assign bending stress \((f)\) and \(E_j\) values to timber sorted according to its \(E_p\) values. The sorting is done by applying a fixed load to the face of the timber and measuring the deflection, which is inversely proportional to \(E_p\). With the microstress machine the deflection is measured continuously over a span of 914.4 mm and each piece is graded according to the lowest \(E_p\) value recorded.

Thus in research into the effects of forest management and tree breeding programmes on resultant wood quality the machine can play a valuable role because it assesses the combined effect of all characteristics which affect stiffness and strength including wood density. Visual grading, because it can assess only readily seen and definable defects such as knots, is a much less useful grading method for research purposes.

The various studies are reported in UDD Reports 20, 21 and 27 (Whiteside, 1972, 1973; Whiteside et al., 1972) and by Whiteside (1974a).

The major findings of the studies undertaken, as they relate to the Kaingaroa Forest resource, are as follows:

1. For all stands, grade recoveries were much better with machine grading than with visual grading. However, the rating of stands by visual grade results correlated very closely with the rating according to machine grade results. This indicates that the variation in results between stands, which was considerable, was due mainly to factors other than wood density because, while the effect of density is automatically taken account of in machine grading, it is ignored in visual grading. In fact, the mean density figures for the stands sampled were very uniform.

2. The rating of quality of stands according to visual and machine stress grading results tended to follow the individual stand stockings, with the higher-stocked stands giving the better results and the lower-stocked stands the poorer results. This is clearly due to the smaller average branch size in the higher-stocked stands. First thinnings from well-stocked 2.4 \(\times\) 2.4 m planted stands were little
inferior in quality to first thinnings from 1.8 × 1.8 m planted stands, indicating that 2.4 × 2.4 m initial spacing results in good timber quality provided that full stocking is maintained up to the time of first thinning. It was found that it is the quality of the large-sized trees in a stand that deteriorates markedly as stand stocking decreases. Such trees, which are frequently associated with gaps or openings in the stand, generally have conspicuously larger branches than the remaining trees, and yield timber of poor quality. On the other hand, the small suppressed trees yield timber of uniformly good quality, even in stands of quite low stocking.

(3) Visual and machine stress-grade results in general improve with increasing height up the tree. The grades are generally better for small-diameter logs than for large-diameter logs, presumably because of the generally larger average branch size in the large logs.

(4) Cross-grain associated with knots is a serious degrading defect in Douglas fir. The larger sized knots are much more likely to have cross-grain associated with them than are the small knots.

(5) Visual and machine stress-grade results for all Douglas fir stands at Kaingaroa, even the poorly stocked stands, are substantially better than for the Kaingaroa radiata pine old crop stands. In most cases machine grading results for cut-of-log Douglas fir are better than for No. 1 framing grade in radiata pine.

(6) Machine stress-grading results show that the inclusion in visual grading rules of provisions for pith, latewood percentage, or growth rate are unnecessary. A high proportion of Kaingaroa Douglas fir has fewer than two rings per centimetre and/or contains pith. However, such timber, provided it conforms to grading rule provisions covering knots and other defects, generally conforms to stiffness and strength requirements. Similarly, latewood percentage could not be shown to affect stiffness and strength to any significant extent, and in any event is too difficult to measure precisely, particularly in pieces cut from near the pith. The proposed new visual stress-grading rules for Douglas fir, to be included in the revision of the New Zealand standard grading rules NZS 3631, contain no provisions for pith, growth rate, or latewood percentage.

(7) In summary, the studies undertaken highlighted the importance of branch size and associated cross-grain as fac-
tors affecting timber stiffness and strength. They also illustrated the lack of importance of growth rate and late-wood percentage as factors affecting stiffness and strength. Therefore it was clear that within a stand these factors did not have nearly the effect on wood density and hence strength that has been widely believed.

Studies on Effect of Tree Characteristics on Sawn Timber Quality

Two detailed studies were made to quantify the relative importance of branch size, wood density, stem straightness, branching habit, and log size on timber yield and quality.

(a) 1970 tree morphology and wood density study: The first study, reported in full by Shelbourne et al. (1973), was based on thirty-two 45-year-old trees from an unthinned stand in Kaingaroa Forest. One of the objectives of the study was to determine which tree characteristics should be emphasised in a Douglas fir tree-breeding programme.

The sample trees were selected in eight character groups, with two trees chosen for high values and two for low values within each group (Table 1). Characters other than those selected for extreme values were generally maintained within about one standard deviation from the stand average.

All branching and bole characteristics were measured after the selected trees had been felled and cross-cut into 4.9 m log lengths, and discs were taken at 4.9 m intervals up the tree for wood density determinations. Four logs from each tree, 128 in all, were sawn to maximise production of 50 mm material in 300, 200, and 100 mm widths. All this material was visually graded, gauged to standard green gauged dimensions, and machine stress-graded. The 200 mm and 300 mm widths were

TABLE 1: CHARACTERISTICS OF 32 SAMPLE TREES USED IN 1970 STUDY

<table>
<thead>
<tr>
<th>Extreme tree types</th>
<th>High values (“good” trees)</th>
<th>Low values (“bad” trees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bole kinks</td>
<td>straight</td>
<td>very sinuous</td>
</tr>
<tr>
<td>Bole sweep</td>
<td>straight</td>
<td>very swept</td>
</tr>
<tr>
<td>Branch diameter</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>Branch angle</td>
<td>flat</td>
<td>steep</td>
</tr>
<tr>
<td>Branch number per cluster</td>
<td>few</td>
<td>many</td>
</tr>
<tr>
<td>Branch distribution</td>
<td>evenly scattered</td>
<td>uninodeal</td>
</tr>
<tr>
<td>Wood density</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Tree diameter</td>
<td>large</td>
<td>small</td>
</tr>
</tbody>
</table>
then resawn to 100 mm width and regraded visually and by the stress-grading machine.

Simple comparisons of the mean timber stiffness ($E_p$) from the two "good" and two "bad" trees in each group were unsatisfactory for elucidating differences between trees, as the effects of other characteristics were frequently confounded with those of the character under consideration. Stepwise multiple regression analysis was used to identify the tree morphology variables having the greatest influence on timber $E_p$ as recorded by the stress-grading machine.

Multiple regressions of average $E_p$ for all 100 × 50 mm pieces, computed separately for each log height class, showed that most of the accountable variation in $E_p$ could be attributed to branch diameter, and that wood density was the next most important characteristic. In the first log height class (i.e., butt logs) branch diameter, wood density, stem deviations, and number of branches per cluster accounted for 82% of the variation ($R^2=0.82$) in mean $E_p$, the prediction equation being:

$$E_p \text{ (gigapascals)} = 4.499 - 0.08088 \text{ branch index (mm)} + 0.01679 \text{ density (kg/m}^3\text{)} - 0.01724 \text{ deviation from straightness (mm)} - 0.151 \text{ number of branches per cluster}.$$

In this equation $E_p$ is the mean $E_p$ of all pieces cut from a log, density is the mean density of the timber pieces, and the other factors relate to the log concerned. Branch index is the index of branch size and is determined by measuring the largest branch per quartile per 1.2 m length, and averaging the 16 measurements so obtained for each 4.8 m log.

The $R^2$ value decreased with increasing height up the tree until, in the fourth log, the factors listed in the regression equation accounted for only 56% of the variation in mean $E_p$. Branch index varied much less among the upper logs, and correspondingly accounted for progressively less of the variation. The relationship of $E_p$ to tree morphology variables was less consistent for 200 mm and 300 mm wide material, but followed the same pattern.

(b) 1974 branch size and wood density study: The second study, aspects of which have been reported by Wilcox (1974b), Tustin and Wilcox (1974), and Whiteside (1974b), was based on 23 second logs, each 4.8 m long. The logs were cut from 51-year-old trees in Compartment 1102 Kaingarofa Forest. This stand was planted in 1923 at 2.4 × 2.4 m spacing and extraction-thinned to a stocking of 320 stems/ha in 1964.

The 23 sample trees were not randomly chosen but were carefully selected for the sole purpose of elucidating the relative importance of the effect of branch index and wood density
on timber modulus of elasticity \( (E_p) \). One hundred straight trees within the diameter-at-breast-height range 50 to 62 cm were provisionally selected in the stand. Basic wood density of the outer 10 growth rings at breast height was determined for each tree from a sample of four 5 mm increment cores. Branch index was measured on the second log of each tree. Butt logs were not used in the study because of the difficulty of accurately measuring their branch indices — most branches in the bottom 4 m had been knocked off in the thinning operation 10 years earlier. Based on the branch and density measurements of the 100 trees, 23 trees were chosen to fit non-overlapping, equally separated classes as shown in Table 2.

**TABLE 2: CHARACTERISTICS OF 23 SAMPLE TREES USED IN 1974 STUDY**

<table>
<thead>
<tr>
<th>Basic density of outer wood at breast height (kg/m³)</th>
<th>Branch index of second logs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small (18-28 mm)</td>
</tr>
<tr>
<td>Low (380-410)</td>
<td>2</td>
</tr>
<tr>
<td>Medium (430-450)</td>
<td>3</td>
</tr>
<tr>
<td>High (480-510)</td>
<td>2</td>
</tr>
</tbody>
</table>

All 23 logs were flat sawn to 100 × 50 mm timber. The green timber was gauged and then machine stress-graded. A sample of clear timber 50 mm long was cut from the end of every piece of timber for density and ring width determination. In all, 398 pieces of 100 × 50 mm timber were cut from the logs, but 21 pieces less than 3 m long were subsequently excluded from the grading study. Thus, the 377 pieces subjected to statistical analysis varied little in length.

The mean \( E_p \) values for each wood density class, each branch index class, and each wood density-branch index subclass are shown in Table 3.

**TABLE 3: MEAN \( E_p \) VALUES (GIGAPASCALS) OF 100 × 50 mm TIMBER SAWN FROM LOGS CLASSIFIED BY DENSITY AND BRANCH INDEX**

<table>
<thead>
<tr>
<th>Density class</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Density class mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>5.82</td>
<td>4.98</td>
<td>4.05</td>
<td>4.94</td>
</tr>
<tr>
<td>Medium</td>
<td>6.00</td>
<td>5.92</td>
<td>4.69</td>
<td>5.54</td>
</tr>
<tr>
<td>High</td>
<td>6.38</td>
<td>5.44</td>
<td>4.84</td>
<td>5.55</td>
</tr>
<tr>
<td>Branch index</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>class mean</td>
<td>6.07</td>
<td>5.45</td>
<td>4.52</td>
<td>5.34</td>
</tr>
</tbody>
</table>
Full statistical analysis of the data (Wilcox, 1974b) confirmed what is readily apparent from the results shown in Table 3, namely, that the effect of branch index on timber stiffness was highly significant, strongly linear, and more clearcut than the effect of wood density. Except for the anomalously high $E_p$ values of timber from the logs classified a “medium density-medium branch index”, the effects of density and branch index were linear and additive. The aforementioned discrepancy can probably be attributed to the necessarily indirect method of assigning second logs to density classes based on density measurements at breast height. The linear correlation between second log mean density and breast height outerwood density was only 0.69.

Table 4 gives machine stress-grade recoveries for timber from logs with small, medium, and large branch indices, and also from logs from trees with high, medium, and low outerwood densities at breast height. The table illustrates very clearly again the predominant importance of branch size.

A series of multiple regression analyses was made on the 23 log mean values for $E_p$, branch index, wood density, and ring width. It was found (Table 5) that branch index alone explained 66% of the variation in log mean $E_p$ as recorded by machine stress-grading. The addition of mean log wood density to the model increased the precision of the prediction equation considerably, the two-variable model accounting for 80% of the variation in mean $E_p$ among the 23 logs. Inclusion of the third variable, mean ring width, in the model made no significant improvement to the prediction equation, indicating that variation in radial growth rate among these trees had no important effect on timber $E_p$.

The regression analysis thus strongly supported the conclusion of the previous analysis (Table 3) that branch index was of prime importance. Expressing the second set of regression estimates of Table 5 in the more familiar equation form, we can state that the mean $E_p$ of 100 × 50 mm green timber from a log can be estimated from $E_p$ (GPa) = 2.9014 - 0.0705 branch index (mm) + 0.0127 density (kg/m³).

In this study, a decrease of 10 mm in mean branch index thus had about the same positive effect on $E_p$ as an increase in density of 59 kg/m³. Changes of these magnitudes are predicted to independently increase $E_p$ by 0.7 GPa. To further illustrate, in a log with a branch index of 40 mm, mean wood density would have to be 425 kg/m³ to give a mean timber $E_p$ of 5.46 GPa, whereas, in a log with a branch index of 25 mm, mean wood density would have to be only 340 kg/m³ to give the same mean timber $E_p$ value. Large branches can therefore be compensated for by high wood density and vice versa.
### TABLE 4: EFFECTS OF BRANCH INDEX AND OUTERWOOD DENSITY ON MACHINE STRESS-GRADE RECOVERIES (Percentages)

<table>
<thead>
<tr>
<th>Machine stress-grade (MPa)</th>
<th>Corresponding $E_p$ (GPa)</th>
<th>Branch Index</th>
<th>Outerwood Density at Breast Height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Small (MPa)</td>
<td>Medium (MPa)</td>
</tr>
<tr>
<td>7</td>
<td>5.46</td>
<td>87</td>
<td>63</td>
</tr>
<tr>
<td>5.52</td>
<td>4.52</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>4.34</td>
<td>3.70</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>&lt; 4.34</td>
<td>&lt; 3.70</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Mean outerwood density at breast height (kg/m³): 440 443 443 494 442 390 442
Mean wood density from timber samples (kg/m³): 381 404 415 417 404 379 400
Mean branch index (mm): 23 37 51 37 36 39 37

Notes: The current revision of the New Zealand visual grading rules, NZS 3631 (publication pending) recognises an engineering grade and a framing grade in Douglas fir. The engineering grade has a basic working stress in bending ($f$) of 7 MPa in green timber, while the framing grade (standard building grade) can be assigned an $f$ value of 4.34 MPa in green timber. The $f$ value assigned to merchantable grade Douglas fir in the Australia standard AS 0106 (Standards Association of Australia, 1971) is 5.52 MPa. This grade is sorted in New Zealand for export to Australia.
TABLE 5: ESTIMATES OF LINEAR REGRESSION COEFFICIENTS RELATING TIMBER $E_o$ TO BRANCH INDEX, WOOD DENSITY, AND RING WIDTH IN 23 LOGS

<table>
<thead>
<tr>
<th>$\beta_0$ (GPa)</th>
<th>$\beta_1$ (Branch index mm)</th>
<th>$\beta_2$ (Density kg/m³)</th>
<th>$\beta_3$ (Ring width mm/ring)</th>
<th>$R^2$</th>
<th>Error mean square</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4089</td>
<td>-0.0551</td>
<td></td>
<td></td>
<td>0.66</td>
<td>0.2029</td>
</tr>
<tr>
<td>2.9014</td>
<td>-0.0705</td>
<td>0.0127</td>
<td></td>
<td>0.80</td>
<td>0.1268</td>
</tr>
<tr>
<td>4.0669</td>
<td>-0.0658</td>
<td>0.0117</td>
<td>-0.1407</td>
<td>0.81</td>
<td>0.1298</td>
</tr>
</tbody>
</table>

SILVICULTURAL IMPLICATIONS OF STUDIES

The findings from the various studies undertaken which are of most significance as far as Douglas fir silviculture is concerned, are as follows:

(1) Rate of radial growth has very little effect on wood density in wood of the same cambial age, particularly in wood further than about 12 growth rings from the pith. This is an important finding which may help dispel a long and widely held belief which has dominated a great deal of thinking on how Douglas fir stands should be managed for sawn timber production. It is now clear that growth rate need not be restrained in order to maintain wood density at an acceptable level. The new visual grading rules for engineering grade Douglas fir in the current revision of the national grading rules, NZS 3631, contain no provisions whatever on growth rate.

(2) Branch size is the most important factor influencing quality of Douglas fir sawn timber for engineering and framing uses, and wood density is the next most important. Other factors are of little importance. Branch size will be influenced by initial stand spacing, by the standard of establishment, and by the thinning regime adopted, and hence, over at least the all-important bottom two 4.8 m log lengths, can be influenced by the silviculturist to a large degree. Within a stand, wood density is largely genetically controlled and can be influenced by the silviculturist to only a small extent. Trees with below-average wood density could be removed in thinnings, as has been advocated by Harris (1967), but this increases the average density of the final crop only slightly, and the practicality of using wood density as a criterion for thinning is highly questionable.
With visual grading, branch size is limited according to the knot size provisions in the timber grading rules. Knot size in 100 × 50 mm timber, which constitutes a large percentage of current usage, is limited to 20 mm in engineering grade, 37 mm in Australian merchantable grade, and 50 mm in standard building grade. Corresponding branch indices are probably about 5 mm larger than these figures. With machine grading the maximum branch (or knot) size for a particular grade is density-dependent because the machine simultaneously evaluates the sum-total effect of both knot size and density.

By applying the regression given earlier linking $E_p$ (and hence bending strength) to branch index and wood density, we obtain for machine-graded timber maximum branch indices for engineering, merchantable, and standard building grades corresponding to various wood densities. This information is given in Table 6.

<table>
<thead>
<tr>
<th>Mean wood density (kg/m³)</th>
<th>Corresponding outerwood density (kg/m³)</th>
<th>Maximum branch index (mm)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>440</td>
<td>510</td>
<td>43</td>
<td>56</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>420</td>
<td>476</td>
<td>39</td>
<td>53</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>442</td>
<td>36</td>
<td>49</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>380</td>
<td>408</td>
<td>32</td>
<td>45</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>374</td>
<td>29</td>
<td>42</td>
<td>53</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen from Table 6 that with machine grading much larger knots can be accepted for each of the grades listed than with visual grading, particularly where the timber that is machine graded is of high density.

OBJECTIVES OF DOUGLAS FIR SILVICULTURE

The objectives of silviculture of Douglas fir have never been clearly stated by the Forest Service. However, the writers are assuming that the main objective must be to produce as high a yield as possible in engineering grades, as distinct from framing grades for general domestic framing use; framing grades can be produced in abundance from radiata pine plantations, and undoubtedly a lot more economically. Visually graded engineering grade in green Douglas fir has an assigned allowable stress in bending of 7 MPa. It is considered that the ob-
DOUGLAS FIR TIMBER QUALITY

Objective should be to manage Douglas fir stands so that at least 60% of the sawn timber volume produced in framing sizes from the bottom two 4.8 m log lengths conforms to engineering grade if visually graded, or has a bending strength of 7 MPa if machine graded. Stands should be grown as rapidly as possible and on as short a rotation as possible consistent with this objective.

The stipulated 60% is a much higher yield than can possibly be achieved with radiata pine. For Kaingaroa radiata pine old crop stands, the recovery in engineering (7 MPa) grade with visual grading is about 11% and with machine grading is 15 to 17%. These figures are unlikely to be improved upon with second-rotation stands managed under current silvicultural schedules, and may even be worse, except where effective pruning has been carried out.

To obtain 60% recovery in engineering grade from the bottom two log lengths with visual grading, it would be necessary for the branch index to be kept down to about 25 mm. To achieve this index, initial stocking would have to be at least 2000 trees/ha, and this stocking would have to be maintained until the branches over the bottom 9.6 m length had died or become moribund. The figure of 2000 trees/ha is derived from the relationship between stocking and branch size in Douglas fir established by James and Revell (1974).

Maintenance of high stocking until the branches over the bottom two log lengths had died or become moribund would mean delaying first thinning until stand top height was about 21 m, or stand age about 25 years, based on green crown depth studies described by Fenton (1967). This in turn would mean a very slow diameter growth rate for a long period, and a long rotation of over 50 years in order to achieve a reasonably large final-crop tree size. This would almost certainly make the whole economics of growing Douglas fir very unfavourable. In the writers' view, therefore, if visual grading is to be practised, there can probably be no economic justification whatever for growing Douglas fir. Because of the long rotation age required, growing costs would be exorbitant.

The only way to reduce growing costs of Douglas fir to more acceptable levels, and so justify further plantings, is to reduce the rotation age to well below current rotations of 50 to 80 years. This will be a viable proposition only if machine stress-grading is practised so that larger branches, and hence wider spacings and faster diameter growth rates, can be tolerated.

Commercial machine stress-grading has only recently commenced in New Zealand, but prospects are bright for the
fairly wide use of this grading method in the near future. Therefore it is not being fanciful or unrealistic to examine a silviculture for Douglas fir based on the assumption that the sawn timber produced will be machine graded.

Most Douglas fir stands in New Zealand have mean wood densities in the range 360 to 440 kg/m³, or outer wood densities in the range 375 to 510 kg/m³. Assuming a mean wood density of 400 kg/m³, it can be seen from Table 6 that the corresponding branch index for 7 MPa grade with machine grading is 36 mm. Table 4 shows that 63% of pieces from logs with a mean branch index of 37 mm, and having an average density of 404 kg/m³, rated 7 MPa on the machine. From these figures it seems reasonable to conclude, therefore, that, where the branch index does not exceed the appropriate figures given under engineering grade in Table 6, then at least 60% of the sawn timber from logs with that branch index will rate 7 MPa or higher on the machine. The objective of silviculture must therefore be to restrict the branch index over the bottom two 4.8 m log lengths to the appropriate figure given under engineering grade in Table 6, while at the same time promoting as rapid diameter growth as possible.

SILVICULTURE

The management of Douglas fir in State forests of the Rotorua-Taupo region has recently been re-examined and proposals have been made for some changes to the traditional delayed-thinning silviculture (C. J. Mountfort, pers. comm.). A similar review has also been made of the important Douglas fir resources of Golden Downs Forest (B. C. Johnson, pers. comm.). The regimes proposed and currently being evaluated at Kaingaroa for the large areas of young stands now less than 20 year old incorporate waste thinning at age 10 to 15 years. This measure is regarded as essential in maintaining rapid diameter growth and health of these stands, all of which are infected with *Phaeocryptopus gaeumannii*. The optimum timing and severity of the early waste thinning is still rather uncertain. On steep country, where production thinning is not economically feasible, a single heavy waste thinning is being considered. On easier country, a production thinning at age 25 to 30 years can be included in the regime, necessitating a less severe earlier waste thinning.

An example of a regime which involves both wide initial spacing and heavy early thinning, but nevertheless is likely to result in acceptable branch size and hence timber quality in the bottom two 4.8 m logs is as follows:
Variations to this schedule would have to be made in stands currently older than 12 years. It is important that the waste thinning is carried out well before age 20 to keep thinning costs down, to maintain a healthy green crown, and to maintain a reasonable rate of diameter growth.

The early heavy thinning coupled with the wide initial spacing in this schedule will result in larger branches than with present Forest Service regimes where the number of trees planted per hectare is normally more than 2000 and first thinning is usually delayed to beyond age 20. However, evidence from a stand in Kaingaroa Forest that has been thinned even more drastically indicates that the schedule will keep the branch index in the bottom two 4.8 m logs down to the size required to produce 60% engineering (7 MPa) grade with machine grading. The Kaingaroa stand in question is Compartment 1279 which was thinned heavily as a seed stand. Its history is as follows:

1953: Planted 3000 stems/ha  
1960 (Year 7): Waste thinned to 1000 stems/ha  
1964 (Year 11): Waste thinned to 540 stems/ha  
1965 (Year 12): Waste thinned to 222 stems/ha

Measurements of this stand were made in 1976 (age 23) to determine the present characteristics of the stand. Results were as follows:

<table>
<thead>
<tr>
<th>Log 1</th>
<th>Log 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch index (mm)</td>
<td>29</td>
</tr>
<tr>
<td>Mean log density (kg/m³)</td>
<td>407</td>
</tr>
<tr>
<td>Predicted mean timber $E_p$ (GPa)</td>
<td>6.02</td>
</tr>
<tr>
<td>Corresponding mean machine stress-grade (MPa)</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Perhaps surprisingly, both the first and second logs are predicted to yield timber with an average machine stress-grade above the 7 MPa level goal. Branch diameter growth has ceased in the first log (all branches are dead) and is clearly near its maximum in the second log. This can be assumed from the fact that the green crowns of adjoining trees are in close contact up to the height of the top of the second log.
(9.6 m). In this stand wood density is as high as or higher than that of most Kaingaroa Douglas fir of more than twice the age, and this has helped maintain timber stiffness and strength at the level required. There is some evidence that the early heavy thinning has resulted in an increase in wood density (Birt, 1972).

An even more heavily thinned part of this stand (138 stems/ha) gave the following results:

<table>
<thead>
<tr>
<th>Branch index (mm)</th>
<th>42</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean log density (kg/m³)</td>
<td>424</td>
<td>415</td>
</tr>
<tr>
<td>Predicted mean timber $E$, (GPa)</td>
<td>5.32</td>
<td>5.07</td>
</tr>
<tr>
<td>Corresponding mean machine stress-grade (MPa)</td>
<td>6.85</td>
<td>6.47</td>
</tr>
</tbody>
</table>

In this stand the branches have become too large to meet the suggested requirement of a mean machine stress-grade level of 7 MPa, even though the wood density is somewhat higher than in the areas of the stand that have been less heavily thinned.

It is therefore apparent that heavy early thinnings to waste currently being considered will result in satisfactory timber quality with machine stress-grading, and should enable stands to be grown on considerably shorter rotations than previously thought necessary (Fenton, 1976). A further cause for optimism about the early and heavy thinning regimes is that the needle cast disease associated with $P. gaeumannii$ is noticeably less severe in the heavily thinned areas of Compartment 1279 than is usual in Kaingaroa Forest.

It should be stressed that the silvicultural schedule listed in this section of the paper is put forward only as an example of a regime incorporating wide initial spacing and early heavy thinning, but which nevertheless meets quality constraints as far as branch size is concerned. This is assuming the sawn timber produced is machine stress-graded. The schedule has not been subject to any economic evaluation, and therefore certainly cannot be recommended for general adoption. The purpose in including it in the paper is to get more foresters and forest economists thinking about silvicultural regimes for Douglas fir which are radically different from those generally being applied at present.

The authors would like to end with a suggestion that measurements of branch diameters and wood density be included in assessment of all thinning experiments, several of which have been established recently in young Douglas fir stands. This will allow evaluation of the timber quality as well as yield results of various thinning treatments.
REFERENCES


