PREDICTING THE IMPACT OF SILVICULTURAL TREATMENT ON THE WOOD CHARACTERISTICS OF *PINUS RADIATA*

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ABSTRACT

The impact of silviculture on intrinsic wood properties can be estimated by separating the analysis into two stages: predicting the impact of silviculture on the distribution of volume according to the physiological age of the wood; and predicting mean-tree wood properties from the mean physiological age of the tree.

A simple growth model provided satisfactory estimates of mean physiological age of trees in two heavily thinned plots of **Pinus radiata** D.Don. The model was used to predict the mean physiological age of trees from selected regimes.

INTRODUCTION

There is concern that the trend towards short-rotation crops (20 to 29 years depending on site) of the kind suggested by Fenton and Sutton (1968) for *Pinus radiata* in New Zealand will result in trees with lower basic wood densities than those from previous silvicultural practices (rotations 35 to 50 years; Harris *et al.*, 1976). Lower densities could in turn cause a noticeable decline in the quality of the structural sawn timber and the pulp produced from sawmill slabs and top logs (Harris and Nash, 1972). Further, recent research suggests that pulpwood crops may be the cheapest source of *P. radiata* pulpwood, with rotations as low as 16 years possible on high-quality sites (James, 1975). Although there are compelling economic reasons for adopting the short rotations (Fenton, 1972; Grant, 1976), there is concern that the impact of the different intrinsic wood properties[1] on the quality of the products derived from these crops may offset the reductions in growing costs.

Some forests are being managed for short-rotation crops, but the regimes are largely untested and there are as yet no final-crop stands. Because the growth of the modern "open grown" crops is so different from that of trees produced on traditional silvicultural schedules, some differences in the distribution of wood by physiological age (defined here as number of rings from the pith) can be expected. Insight into the wood qualities of crops from these untested silvicultural regimes can be gained by modelling the patterns of growth and form of the trees these regimes will produce.

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[1] The properties of clear, knot-free wood.

Role of Physiological Age

Although the impact of branch size on quality of structural timber produced from short-rotation crops has been considered, it has not been possible to measure the effect of lower wood density. Preliminary work on 100 × 50-mm structural timber indicates that, given the size of the branches in a log, it is possible to derive a good relationship between the mean basic density of the log and the machine stress grade of the timber the log produces (Harris *et al.,* 1976). Accordingly, by predicting the mean basic density of the sawlogs from short-rotation regimes it will be possible to assess the quality of the structural timber they will produce.

Since most New Zealand market pulps are (and probably will be) used for blending, tear index is likely to be the factor limiting international sales of New Zealand kraft pulps produced from short-rotation crops (Uprichard, 1975). For mechanical pulps the situation is less clearcut, but tensile index appears to be a crucial characteristic (Corson, 1975). Both the tear index of kraft pulps and the tensile index of mechanical pulps are improved by increasing the basic wood density and tracheid length of the wood used for pulping (Uprichard, 1973). Pulp yield per cubic metre of wood and yield per digester load are also improved by increasing basic wood density.

In turn, these factors increase with increasing physiological age of the wood (increasing number of rings from the pith). Consequently, both mean tree wood density and mean tree tracheid length are dependent on the distribution of wood by physiological age within the tree.

Harris (1965), in an examination of 317 twenty-six-year-old *P. radiata* trees on 33 sites in New Zealand, identified three broad classifications of trees, those with:

(1) High corewood density and high outerwood density;
(2) Low corewood density and high outerwood density;
(3) Low corewood density and low outerwood density.

It is apparent from Harris and Nash (1972) that, for any given site, sorting trees into even two classifications — high and low corewood density — can substantially reduce the variation in basic wood density not explained by physiological age. In such circumstances good linear correlations between basic wood density and physiological age of individual trees can be obtained for trees up to 25 years old on central North Island sites (J. M. Harris, pers. comm.). On other sites preliminary evidence suggests that the relationship between basic wood density and physiological age over this time-span may be curvilinear and best approximated by a quadratic or by two piecewise linear functions (D. J. Cown, pers. comm.).

Further, apart from some studies on nutrient-deficient sites, no major change has been observed in the basic density of wood produced immediately after thinning in spite of the increased radial growth that thinning engenders (Cown, 1973; 1974; Sutton and Harris, 1974). However, wood produced after pruning has been found to be of slightly higher density than otherwise expected (Cown, 1973). By far the most important differences in intrinsic wood properties between regimes arise from differences in the distribution of wood by physiological age (Harris *et al.,* 1976).

Thus a relationship between basic wood density and physiological age of the wood for a given site can be expected to provide a good indication of the mean basic wood density for trees in both thinned and unthinned stands on that site, although the estimate of density after pruning may be slightly conservative.

Tracheid length at breast height increases with physiological age until about 15 years, after which tracheid length remains more or less constant (Cown, 1975). Although tracheid length varies with height in the tree, the effect on mean tracheid length of the tree of assuming a single relationship between tracheid length and physiological age at all levels within the tree is negligible when comparing crops (Harris, 1975). Consequently, good estimates of the average tracheid length of a whole tree can be obtained from transformed linear or quadratic functions of the mean physiological age of the tree.[2]

The considerable variation in wood properties with location and seed source require separate wood-density/physiological-age and tracheid-length/physiological-age relationships for each site. However, once these relationships are established the two-stage technique of estimating the impact of the silviculture on mean physiological age and then estimating the wood properties has considerable advantages. For example, in analysing the impact of silviculture on wood properties it removes the effect of climate, altitude, latitude, and genetic origin. In experiments designed to directly relate silvicultural treatment to wood properties these factors would increase the observed variation in wood properties and mask the impact of the silvicultural practice.

A BASIS FOR A PREDICTIVE MODEL

In predicting stand characteristics it is necessary to decide whether the model should be of a complete stand, the mean tree of the stand, or the summation of models of individual trees in the stand. Necessity for choice can be avoided if it is possible to describe the growth pattern of a stand in such a way that the plot average is a good representation of the growth of individual trees in the stand.

In this respect short-rotation crops of the kind suggested by Fenton and Sutton (1968) have the special characteristic that, because of the heavy early thinning, there is little competition between trees. Accordingly the final crop does not divide itself

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[2] With linear relationships between wood properties and physiological age, the mean wood properties of a tree can be estimated from a knowledge of the mean physiological age of the tree. For relationships where the mean physiological age term is a transformed term, it is necessary to calculate the mean transformed physiological age to estimate wood properties using that relationship.

However, many of the relationships between wood properties and physiological age can be approximated by a quadratic function of the form:

wood property $(w) = ax^2 + bx + c$

a,b,c constants

x mean physiological age

Considering this relationship as:

$$dw/dx = 2ax + b$$

reduces the problem to a linear form and enables the use of the arithmetic mean physiological age. Estimates of the mean wood properties of the tree can be derived by integrating this equation and setting the constant of integration equal to the wood property of age zero wood (derived from empirical studies). The equation containing the derivative may also be an appropriate vehicle for studying wood properties since it is the rate of change of wood properties with physiological age which is of interest.

into dominance classes and from age 4 years the growth of the average tree of the stand parallels the growth of individual trees in the final crop. Hence the mean physiological age of the average tree is likely to be a good predictor of the mean physiological age of the whole crop.

Further, where final crops receive a heavy early thinning there is also less variation between trees in height growth than under more traditional treatments. Thus for heavily thinned crops, estimates of stand height, such as predominant mean height or mean top height, can be used as reasonable estimates of the height of individual trees in the crop.

For other crops such as the pulpwood crops cited by James (1975), the final-crop stockings are much too high for a plot average growth function to be representative of the growth of all trees in the plot. Consequently, it is necessary to either predict the mean physiological age and volume of each tree in the crop or to divide the final crops into growth elements, each with separate diameter and height growth patterns. It is possible to partition such a stand into diameter growth groups using procedures outlined by Beekhuis (1966) or Bailey (1973) and to estimate the pattern of height development for these individual diameter growth groups (Clutter and Allison, 1974).

Having thus obtained estimates of both breast-height diameter and top height for each year, it is necessary to make some assumptions about tree form in order to estimate the distribution of wood by physiological age. Any form function chosen must be capable of representing the form of trees ranging from 4 to 25 years of age. For this reason Gray's (1956) taper line, which contains a simple parabolic form assumption, was used.

Given the annual basal area and height growth (either by direct measurement or by projection), and using Gray's taper line, the tree growth model illustrated in Fig. 1 can be constructed. Following the notation of Balodis (1966), age has been assessed as age from the pith, and the paired co-ordinates in Fig. 1 show the height interval and the physiological age of the wood (number of rings from the pith). Thus the volume of age 1 wood is, from the diagram, the sum of the volumes of the sections 1,1; 2,1; 3,1; 4,1; 5,1 while age 4 wood is the sum of the volume in sections 1,4 and 2,4.

Description of the Data Used for Testing

The only reliable data available to the author for testing models of the distribution of New Zealand-grown *P. radiata* tree volume by the physiological age of the wood is that from stem analyses conducted by McEwen (1976). The data are from sample plot R67 in Compartment 9 in Whakarewarewa State Forest. In this experiment two previously thinned plots (Plots 2 and 4) were felled and detailed stem analyses of each of the trees in the plot were conducted. Table 1 gives the history of the silvicultural treatment of both plots. When multiple-leader trees were excluded, complete stem analysis data were available for 47 trees—26 trees in Plot 2 and 21 trees in Plot 4.

The data included annual measurements of height, diameter at the whorl terminating each year's growth, diameter at breast height, and annual sectional volume between annual height intervals. A summary of these data for each plot is given by McEwen (1976). By using these data, and assuming a frustrum of a cone between each diameter measurement, it was possible to calculate the distribution of tree volume by physiological age and thus the mean physiological age of each tree after each year's growth.

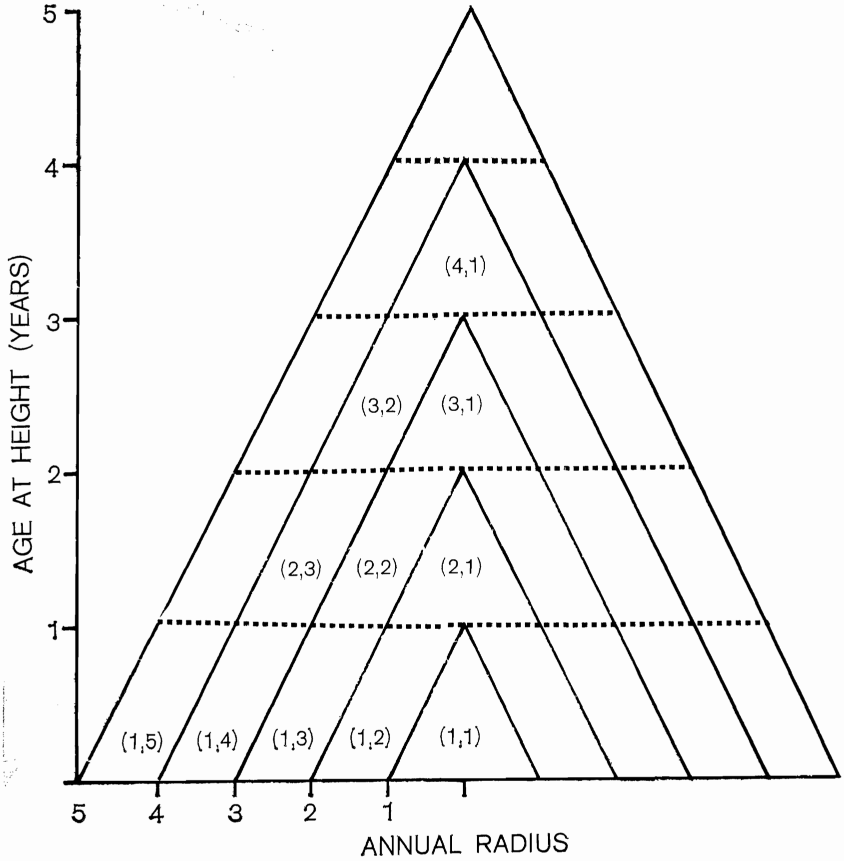

FIG. 1—Schematic representation of tree model.

TABLE 1—Plot history: Experiment R67, Compartment 9, Whakarewarewa State Forest

	Plot 2	Plot 4
Planted	1942	1942
Plot size (ha)	0.1619	0.1214
Initial spacing (m)	1.83 × 1.83	1.83 × 1.83
Initial stocking (stems/ha)	2380	2900
Stocking at age 9* (stems/ha)	1872	2331
Thinned at age 9 to (stems/ha)	692	791
Thinned at age 15 to (stems/ha)	291	388
Thinned at age 22 to (stems/ha)	173	240

* At age 6 the stand was given a low pruning (about 2.5 m) and a light thinning of suppressed trees. Some mortality due to **Sirex noctilio** wood wasp also occurred. A full description of both the stand and these plots is given by McEwen (1976).

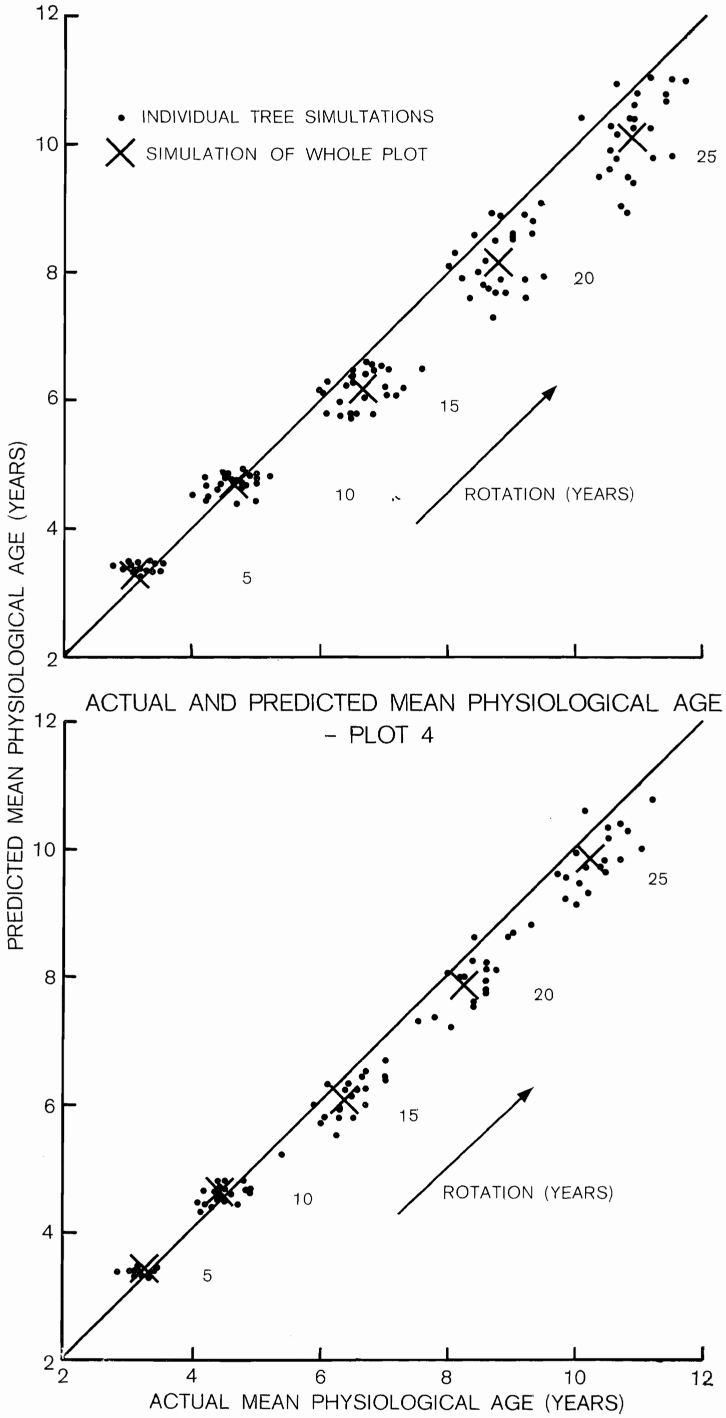

FIG. 2—Actual and predicted mean physiological age (Plot 2 above)

Test of the Technique

Using the basal area measurements from McEwen (1976), a height/age relationship given by C. J. Goulding (pers. comm.), and Gray's taper line, the model was used to estimate the mean physiological age of both individual trees and the average tree in each plot. The height/age function of Goulding[3] progressively underestimated the height of the trees after age 20; the resulting estimates of mean physiological age were therefore also progressively underestimated from age 20. Since this analysis is a test of the technique rather than of the height/age relationship, a simple linear trend which corrected the underestimated heights was added to the height/age function. This alteration significantly reduced the bias of the model for rotations over 20 years, although Fig. 2 and 3 show that some error in the estimate of mean physiological age remains.

Following Freese (1960) it is possible to attribute the inaccuracy of the predictions

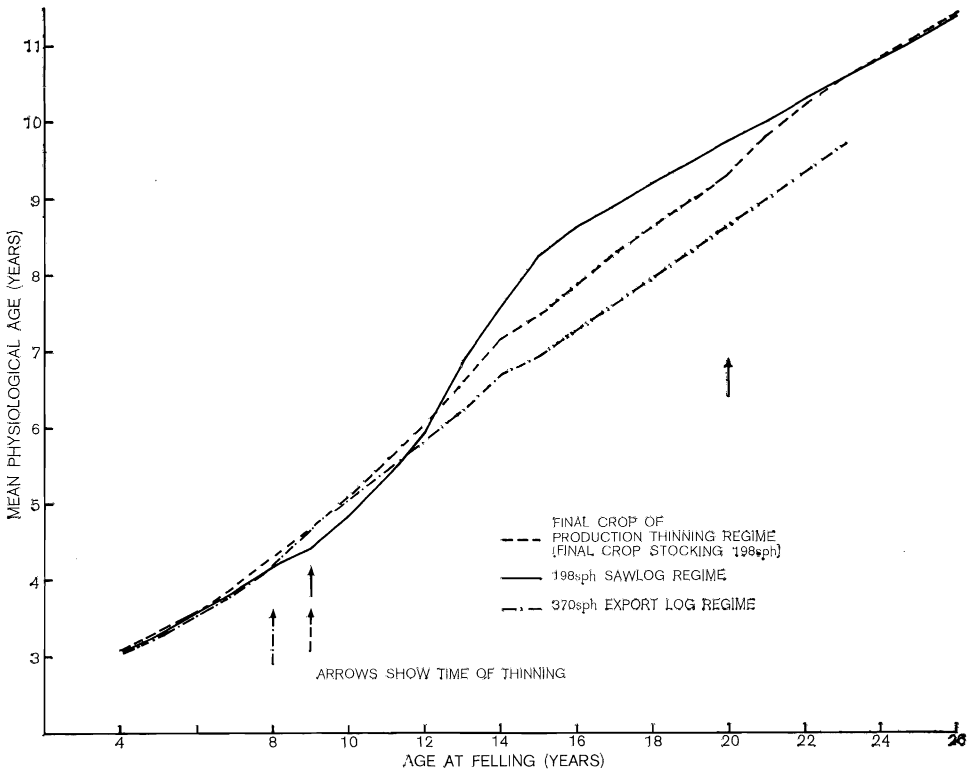

FIG. 3—Change in mean physiological age of **P. radiata** with rotation age: predictions for selected regimes on site index 29 m.

[3] The height/age function supplied by Goulding was of the form

height (H) = k (i — exp(—(a + bS) A²))

where S is the site index and A is the age. Although not formally published or authenticated this function is widely used in forest management.

to bias and/or to imprecision. It is also possible to estimate the likely precision of the predictions if any bias was removed[4]. The results of this analysis are presented in Table 2. As the figures suggest, the model overestimates by 6-8% the mean physiological age of 5-year rotations, provides a good estimate of the mean physiological age for 10-year rotations, and underestimates by 5-7% the mean physiological age of rotations from 15 to 25 years. Given the quality of the silvicultural data available for the regimes under investigation, this is an acceptable level of accuracy.[5]

TABLE 2—Accuracy of the projections of mean physiological age

	Plot	Rotation (years)				
		5	10	15	20	25
Bias as a percentage of mean	2	8	1	—7	—7	—6
physiological age	4	6	3	—5	—5	—5
Percentage of total variation	2	63	2	56	54	59
attributable to bias	4	65	25	65	70	67
Chi-square test with bias	2	32.8	39.0†	36.0	36.5	27.8
removed*	4	14.8	18.0	11.6	9.4	9.2

* Where the desired level of accuracy has been set at 10% of the mean.
† Statistically significant ($P \leq 0.05$).

PREDICTIONS FOR SAWLOG REGIMES

The annual growth in basal area per hectare has been published for the 198 stems/ha short-rotation sawlog regime (Fenton, 1972), the 370 stems/ha export log regime (Fenton and Tustin, 1972), and the final-crop component of the production-thinning regime (Fenton *et al.*, 1972). It is important to remember that these are nominal regimes and that only estimates are available of both the basal area development and the height/age functions which are the basis for the projections of mean physiological age.

Projections of mean physiological age for crops produced under all three silvicultural regimes are given in Fig. 3. From age 23 there is little difference in the mean physiological age of trees produced either as the final crop of the production-thinning regime or under the short-rotation sawlog regime. This lack of distinction can be attributed

[4] Assuming a 10% level of accuracy is required.
[5] In fact Table 2 shows that, except for 10-year rotations where the model is a good predictor, most (54-70%) of the variation between the predicted and the actual mean physiological age is attributable to bias. Additions to the model to incorporate the increased taper associated with both butt swelling and the green crown would both tend to increase the predictions of mean physiological age and thus reduce the bias. If the bias could be removed by these and/or other refinements, the chi-square tests given in Table 3 indicate that the model would perform extremely well. Indeed, at the 10% level there is only one instance when there would be a significant difference between the predicted and the actual mean physiological age.

to the similar pattern of basal area development of both crop types for, although the regimes produce trees of different sizes, they have a similar percentage growth in basal area from age 20.

Thus, within the limits of the projections, the effect on intrinsic wood properties of adopting the short-rotation regime over production-thinning regimes will be almost equivalent to the impact of felling the latter crop at age 26 (the felling age for the short-rotation regime).

However, Fig. 3 also shows differences in mean physiological age between the export log regimes and the other regimes. At the same age of felling the export log regime consistently has a mean physiological age 1 to 1½ years less than the short-rotation sawlog regime.

For Kaingaroa sites basic wood density of the tree can be approximated by a linear function increasing (from a base of about 340 kg/m^3) by 4 kg/m^3 with every year in mean physiological age (Harris, 1975). Each year in mean physiological age is roughly equivalent to a 1-2% change in basic wood density of the tree.

Thus age for age, the export log regime has a 2% lower basic density than the sawlog regime on these sites, and at their economic rotations the difference in their basic density is approximately 4%.

DISCUSSION AND CONCLUSIONS

Estimates of the basal area development of the final-crop trees of the short-rotation sawlog regime, the export log regime, and the production-thinning regime have been published (Fenton, 1972; Fenton *et al.*, 1971; 1972). Because of the low final-crop stocking of these regimes it is reasonable to assume that there is little competition between trees. Thus a single growth function for both height and basal area can be used for each regime.

It is pertinent to point out that there is considerable uncertainty about the appropriateness of the paraboloid form assumptions inherent in Gray's taper line. Although Gray's taper line appears to be a good description of tree form over a wide range of species and spacings in Britain (Gray, 1956; Whyte, 1965), it has not been widely used in New Zealand. No statistical evidence has been presented to show changes in tree form with silvicultural treatment but there are some suggestions that such changes occur (Fenton *et al.*, 1971). In particular the butt swelling commonly associated with *P. radiata* in New Zealand is not included in Gray's taper line. As well as being a significant volume in older trees, the butt swelling contains the wood of greatest physiological age. In fact it is probably because of the failure to incorporate the butt swelling that the model consistently under-predicts the mean physiological age of trees more than 20 years old.[6]

The use of mean physiological age also deserves some comment because it assumes that wood properties are additive. Thus, it is assumed that pulp properties, for example,

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[6] The model uses breast-height diameter and top height to derive the appropriate taper line. At older ages any butt swelling could extend past breast height, and breast height diameter may therefore include a butt swelling component. In this way the model may partly compensate for the butt swelling.

can be predicted from a knowledge of the average[7] intrinsic properties of the wood being pulped. Such an assumption is not valid for all wood products. For judging bending strength in poles, for example, the density of wood in the annulus described by the outer 10% of the pole's radius is 200 times more important than the density of the central cylinder of the same radius.[8]

Accordingly some care must be taken in using mean physiological age to derive wood properties and in subsequently using these predictions to comment on the quality of the wood products produced from differing silvicultural regimes.

Notwithstanding these qualifications it is possible, using mean physiological age, to analyse the impact of silviculture on the growth pattern of the tree and, from this information, to build a simple model for predicting the effect of silviculture on intrinsic wood properties. If the model can predict mean physiological age to within 10% (a requirement which appears to be within the capability of the model reported here) then mean tree density of 20- to 25-year rotations can be estimated to within 1% if no variation in density within physiological age is considered.

With the provision of height growth data for pulpwood crops, this technique offers the possibility of predicting intrinsic wood properties from a wide range of silvicultural practices. Coupled with the effect of site on wood properties (documented by Harris (1965) and currently under review) it is likely that reasonable estimates can be made of the intrinsic wood properties for alternative silvicultural regimes on most sites in New Zealand.

Research into the effect of wood properties on sawn timber and pulp quality is currently proceeding and the techniques described in this paper offer a method of estimating the quality of some products without waiting for the stands to reach merchantable age.

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[7] Average here should be taken to include both the mean and other measures of central tendency and dispersion.

[8] This follows from: the bending strength of a cylindrical annulus as a percentage of the bending strength of the cylindrical pole is proportional to $(1\text{-}K^4)$ where 1-K is the radius of the annulus expressed as a percentage of the radius of the pole. Therefore the volume of the annulus expressed as a percentage of the volume of the pole is proportional to $(1\text{-}K^2)$.

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