MODELLING OF *PINUS RADIATA* WOOD PROPERTIES. PART 2: BASIC DENSITY

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ABSTRACT

Increment cores (5 mm diameter) and wood discs (50 mm thick) were used to study wood basic density patterns in *Pinus radiata* D. Don in relation to tree age, ring number from pith, position in the stem, and site in about 1000 stems from the North Island of New Zealand. Based on the relationships determined within trees, between trees, and between sites, a model was constructed which can satisfactorily predict wood basic density according to tree age, ring number from pith, and height in the stem at any location, and can explain the main contributions to variations in the wood density of individual trees. Furthermore, the model predicts the average density of given log height classes from data collected from breast height (1.3 m) outerwood increment cores.

The detailed variation of wood density within the tree revealed by the simulation software can be directly applied by industry, e.g., in "growing forward" density predictions for stands assessed prior to harvest, and allocation of stands and log types to alternative processes.

Keywords: wood properties; basic density; modelling; simulation software; *Pinus radiata*.

INTRODUCTION

Wood is characteristically a highly variable material, exhibiting differences in anatomy and physical properties between wood cells, tree rings, individual trees, sites, and geographic regions (Cown *et al.* 1991). Variation in basic wood density is of particular interest to the forest industry as this property is related to a number of solid wood utilisation characteristics (e.g., timber strength and stiffness, machinability, and drying) and manufacture and performance of reconstituted products (e.g., raw material consumption, uptake of chemicals, pulp yields, and paper properties). Wood density is therefore one of the most important qualities for wood and wood products. For *Pinus radiata*, wood density varies not only from tree to tree (between-trees), but also within trees (within-trees). The within-tree variation constitutes a major part of the overall variability that can be expected for one species (Kandeel & Bensend 1969). Other properties (e.g., spiral grain, tracheid length, compression wood, microfibril angle, presence of knots) can be significant for specific end-uses and are dealt with in other reports (Tian *et al.* 1995; Tian & Cown 1995).

Many studies have shown that there is a large within-tree variation in wood quality (Zobel & van Buijtenen 1989), and the variation of wood density in particular makes it difficult to predict its performance precisely (Zhang *et al.* 1993). Therefore, establishing a model to predict the inherent within-tree variation in wood density is desirable for both forest management and efficient wood utilisation. Development of a software package to simulate within-tree variation in wood density would enable a better understanding of the within-tree variation in wood density and provide a basis for studies on wood quality improvement. Although much research has been carried out in New Zealand and elsewhere on the within-tree variation in wood density (Cown 1992), modelling approaches, particularly those aimed at practical application, have rarely been explored. It is well documented that wood density is correlated with tree age, ring number from the pith, stem height, and site (Cown & Parker 1978; Cown 1980, 1992), and so it is logical to model those relationships.

MATERIALS AND METHODS

For the present study, data from breast height increment core samples from hundreds of sites throughout New Zealand (Cown *et al.* 1984, 1991) were re-analysed to generate mathematical functions. In addition, density values from about 1000 individual sample trees from previous studies, mainly from the North Island in New Zealand (e.g., Cown & McConchie 1982), were analysed for within-tree patterns. In particular, a large set of detailed data on 40 trees (23 and 43 years old) from Kaingaroa Forest was used to build the whole-tree model.

ANALYSIS OF VARIATION AND CONSTRUCTION OF WOOD DENSITY MODEL

Density Variation with Ring Number from the Pith

The typical pattern of radial wood density variation for *P. radiata* is a rapid increase with increasing ring number from the pith in the early years, followed by a levelling-off later in life (Fig. 1 and 2). Numerous studies have described this relationship between density and

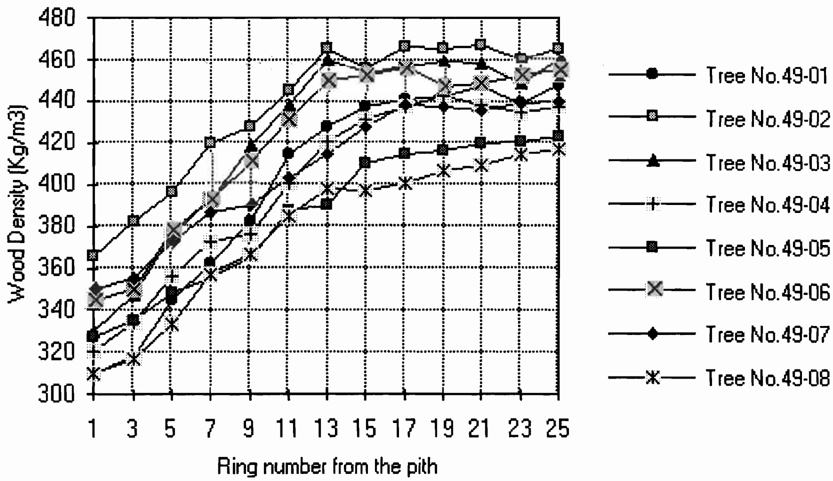


FIG. 1–Radial wood density variation by ring number from the pith, 25-year-old trees.

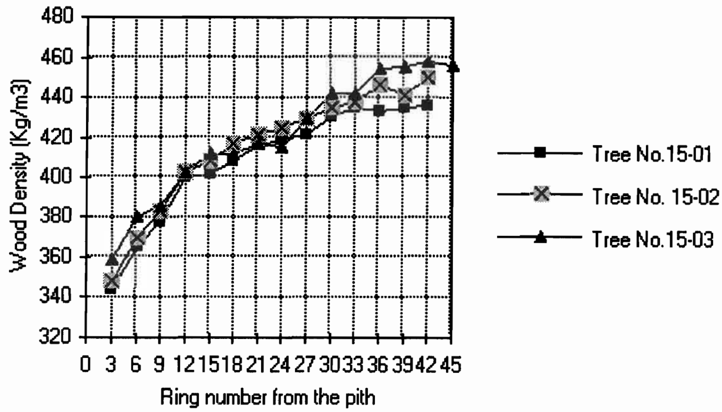


FIG. 2–Radial wood density variation by ring number from the pith, 43-year-old trees.

ring number for *P. radiata* and determined that a linear regression equation (Fig. 3a) is not appropriate. The developmental trend of wood density with ring number is a curve approximating the Logistic curve, and so a Logistic non-linear regression model was selected to simulate the law of density change with ring number from the pith.

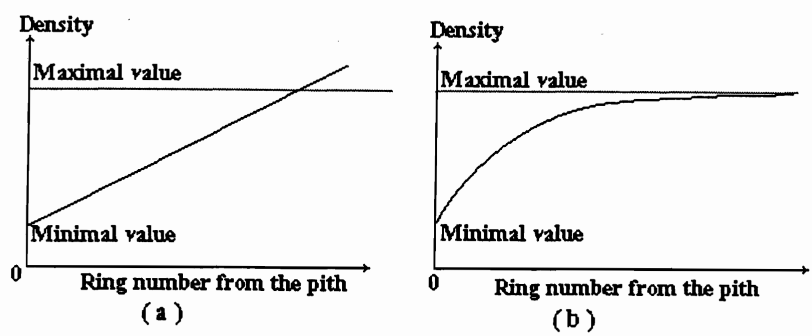


FIG. 3–Comparison of linear and non-linear models for the relationship between wood density and ring number from the pith.

Logistic curve model:

$$\mathbf{y = k / [1 + a \cdot e^{-bx}]} \qquad [1]$$

where **y** is wood density; **k** is the maximum value of wood density and it can be estimated by using the three-point form of equal difference:

$$\mathbf{k = [\, y_2^2 \cdot (y_1 + y_3) - 2\, y_1 y_2 y_3 \,] \,/\, [y_2^2 - y_1 y_3]} \qquad [2]$$

a and **b** can be estimated by using the least square method; then the minimal value (initial value) of the wood density is equal to **k/(1+a)**.

Finally, the fit of the regression equation can be tested using the coefficient of correlation (**R**) and mean square error (σ^2).

$$\mathbf{R} = \sqrt{1 - \Sigma (y_i - \hat{y}_i)^2 / \Sigma (y_i - \bar{y}_i)^2} \qquad [3]$$

$$\sigma^2 = \sqrt{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 / n} \qquad [4]$$

According to Equations 1–4, a model relating average wood density and ring number for 25-year-old *P. radiata* from the central North Island was created using mean values [Equation 5] and plotted in Fig. 4.

$$\mathbf{WD} = \mathbf{455.9883 / [1 + 0.4988 \cdot e^{-0.1443 \cdot RN}]} \qquad [5]$$

where **WD** symbolises wood basic density and **RN** represents ring number from the pith. The mean square error $\sigma^2 = 5.4931$ and the coefficient of correlation **R**= 0.9896.

Similarly, a model between average wood density and ring number is illustrated for 43-year-old *P. radiata* stems from another stand in Kaingaroa Forest [Equation 6] (Fig. 5):

$$\mathbf{WD} = \mathbf{469.5485 / [1 + 0.3508 \cdot e^{-0.0489 \cdot RN}]} \qquad [6]$$

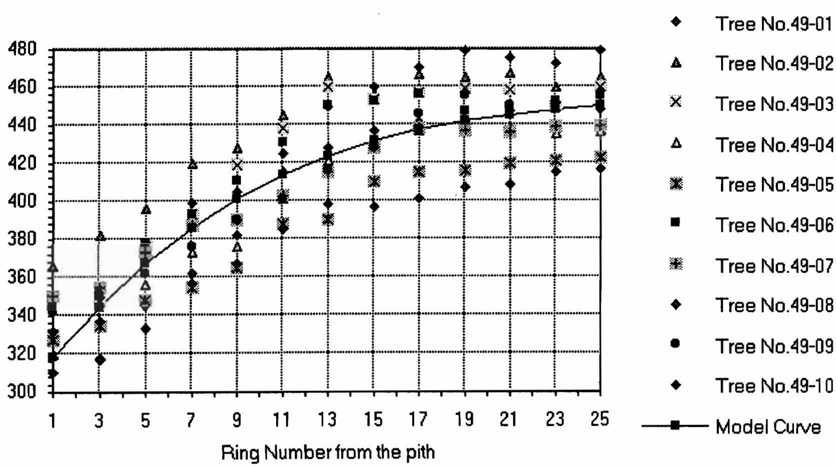


FIG. 4—Measured and predicted wood density based on the Logistic model [Equation 5] for 25-year-old trees.

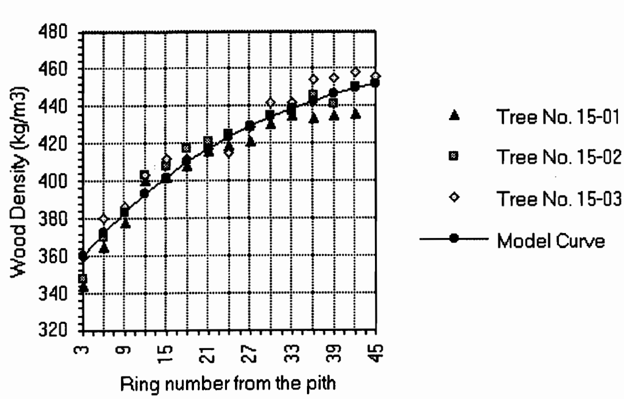


FIG. 5—Measured and predicted wood density based on the Logistic model [Equation 6] for 43-year-old trees.

The mean square error $\sigma^2 = 4.1488$ and the coefficient of correlation $\mathbf{R} = 0.9903$.

These examples [Equations 5 and 6] indicate that the model of wood density by ring number from the pith conforms to the Logistic curve.

Vertical Density Variation with Height in the Stem

Average wood density appears to be high at the base of tree, increases slightly with increasing stem height, then decreases non-linearly to the top of the tree. Differences have been noticed between individual trees, but for most trees studied there is a non-linear (quadratic parabola) relationship (Fig. 6 and 7). A quadratic parabola model was selected to simulate the law of density change with stem height from the butt.

The quadratic parabola model:

$$\mathbf{Y} = \mathbf{a} \cdot \mathbf{X}^2 + \mathbf{b} \cdot \mathbf{X} + \mathbf{c} \qquad [7]$$

where **a**, **b**, and **c** can be estimated by using non-linear regression analysis.

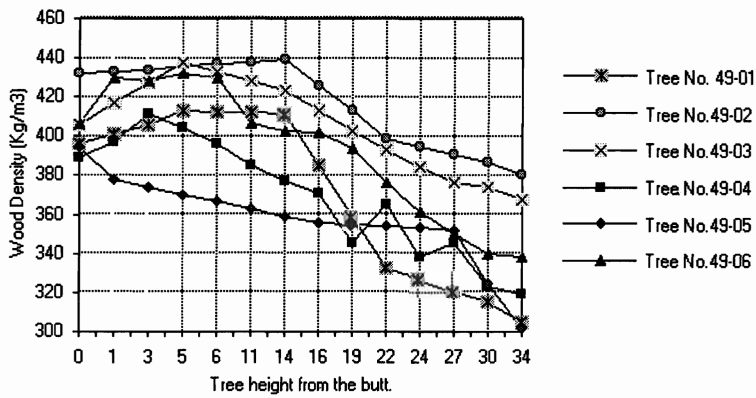


FIG. 6–Vertical variation in average wood density with tree height, 25-year-old trees.

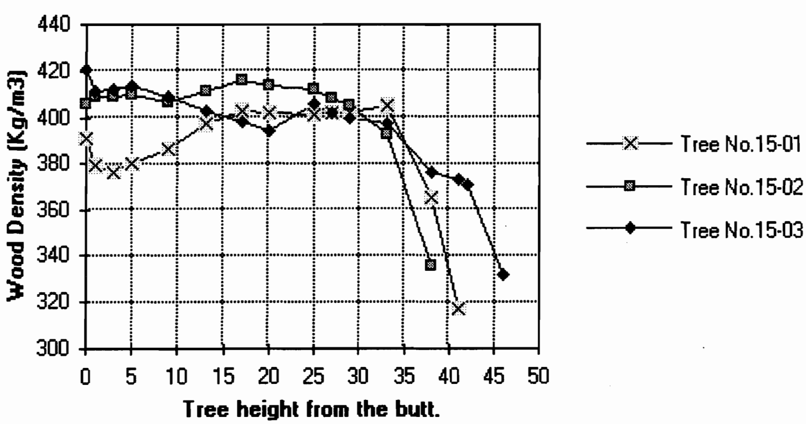


FIG. 7–Vertical variation in average wood density with tree height, 43-year-old trees.

A quadratic parabola model for average wood density and tree height for 25-year-old *P. radiata* from Kaingaroa Forest was created (Fig. 8) using tree mean values and with the form:

$$\mathbf{WD} = -\mathbf{0.0766 \cdot H^2 + 0.2757 \cdot H + 410.1516} \qquad [8]$$

where **WD** symbolises wood basic density and **H** represents tree height (m) from the butt. The mean square error $\sigma^2 = 4.69$ and the coefficient of variation $\mathbf{R} = 0.92$.

Similarly, a model of average wood density and tree height for 43-year-old *P. radiata* from Kaingaroa Forest was created (Fig. 9):

$$\mathbf{WD} = -\mathbf{0.07497 \cdot H^2 + 2.2244 \cdot H + 393.5021} \qquad [9]$$

The mean square error $\sigma^2 = 9.43$ and the correlation coefficient $\mathbf{R} = 0.89$.

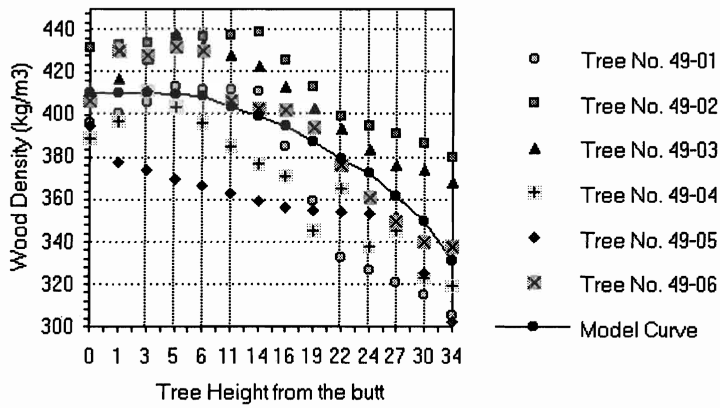


FIG. 8—Measured and predicted wood density based on the quadratic parabola model [Equation 8] for 25-year-old trees.

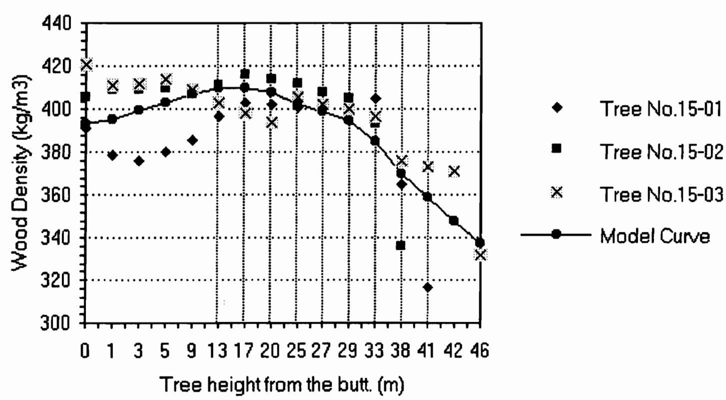


FIG. 9—Measured and predicted wood density based on the quadratic parabola model [Equation 9] for 43-year-old trees.

Geographic Density Variation

The environment has a strong effect on wood density values in New Zealand. Extensive research has demonstrated that average mean annual temperature is the main influencing factor, with contributions from other site factors such as latitude, rainfall, and soil nutrient status (Cown *et al.* 1991).

Regional average breast height wood density patterns of sample trees from several hundred sites are plotted in Fig. 10. Regional models were developed to fit the data: (**WD** = **G1/1[1 + G2·e$^{\mathbf{G3 \cdot RN}}$]**) where **WD** = wood density, **RN** = ring number from the pith, **G1–G3** = model parameters (Table 1, Fig. 11). These regional models clearly confirmed the following:

- Regional averages appeared to fall into three wood density groups—high (Auckland), medium (Rotorua, Nelson), and low (Wellington, Westland, Canterbury, and Southland).
- Average regional differences were more pronounced in the outer rings than the inner rings (juvenile wood).

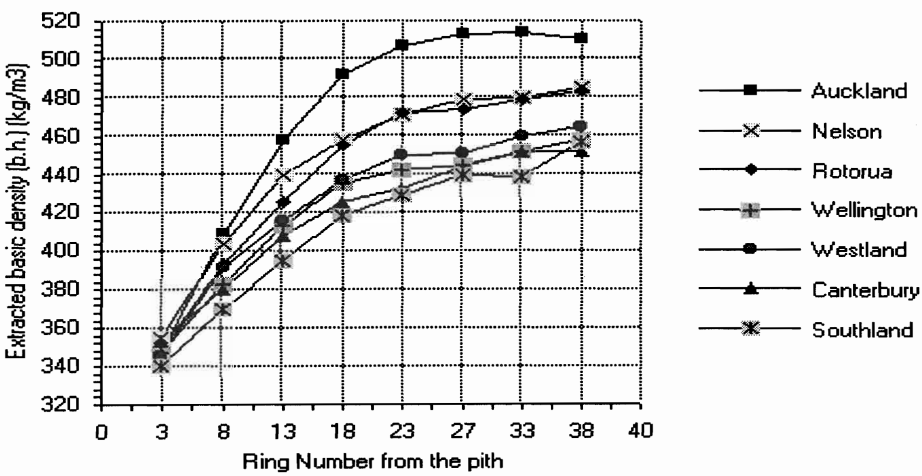


FIG. 10–Regional breast height average wood density models.

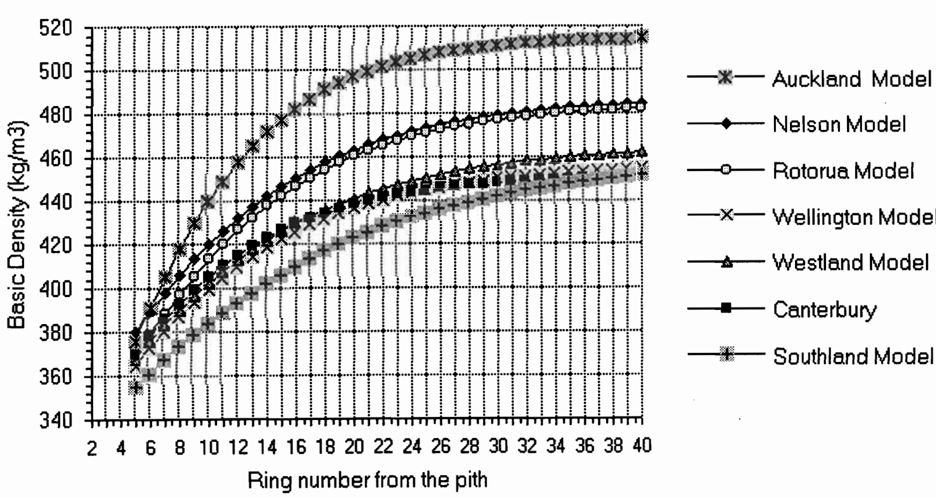


FIG. 11–Regional wood density breast height models.

TABLE 1–Regional wood density models.

Region	Model	σ^2
Auckland	$WD = 515.6212 / [1 + 0.8015 \cdot e^{-0.1539 \cdot RN}]$	4.1488
Nelson	$WD = 487.4623 / [1 + 0.4979 \cdot e^{-0.1132 \cdot RN}]$	3.1325
Rotorua	$WD = 484.7812 / [1 + 0.5723 \cdot e^{-0.1194 \cdot RN}]$	5.3262
Wellington	$WD = 457.3690 / [1 + 0.4414 \cdot e^{-0.1110 \cdot RN}]$	4.2556
Westland	$WD = 465.4959 / [1 + 0.4488 \cdot e^{-0.1050 \cdot RN}]$	2.9275
Canterbury	$WD = 452.1364 / [1 + 0.4299 \cdot e^{-0.1313 \cdot RN}]$	10.5088
Southland	$WD = 459.5329 / [1 + 0.4449 \cdot e^{-0.0817 \cdot RN}]$	3.6003

σ^2 = mean square error

- If juvenile wood were to be defined as a density level (e.g., <400 kg/m^3) rather than a number of rings (e.g., 10 rings from the pith), there would be very significant regional differences.

Variation of Wood Density with Tree Age

Many *P. radiata* wood quality studies have yielded information on wood density at various positions up the stem and attempted to relate the data to log position (based on nominal 5.5-m log lengths) from the butt log to the top of the tree (pulpwood).

Using a modified exponent curve model ($\mathbf{y = a \cdot x^{b/x}}$) and a logarithmic curve model $(\mathbf{a + b \cdot log(x)})$, a group of models for stand average tree and log densities were created from 1674 records describing individual tree densities from 241 sites throughout New Zealand (Cown *et al.* 1991) (Table 2, Fig. 12 and 13).

TABLE 2–Models for log wood densities

Tree component	Model	σ^2
Butt log	$WD = 506.4 \cdot e^{-4.8/AGE}$	3.60
Second log	$WD = 500.0 \cdot e^{-5.6/AGE}$	1.62
Third log	$WD = 500.9 \cdot e^{-6.2/AGE}$	0.74
Fourth log	$WD = 485.9 \cdot e^{-6.0/AGE}$	1.15
All sawlogs	$WD = 491.0 \cdot e^{-5.4/AGE}$	0.93
Pulplogs –		
Tree age <18	$WD = 476.8952 \cdot e^{-4.8/AGE}$	2.98
Tree age ≥18	$WD = 178.3 + 61.2 \cdot \log(AGE)$	1.06
Whole tree	$WD = 476.8952 \cdot e^{-4.8/AGE}$	1.16

WD = wood density
AGE = tree age
σ^2 = mean square error

WITHIN-TREE DENSITY MODEL

To construct the overall pattern of variation in wood density within trees, existing wood sample data from trees in the age range 23–46 years were examined according to height in the stem and radial position. Data from a typical sample tree are given in Table 3.

The two data sets (25- and 43-year-old stands) were used to generate the overall pattern of variation in wood density within stems (Fig. 14a, b). The values in each cell represent the

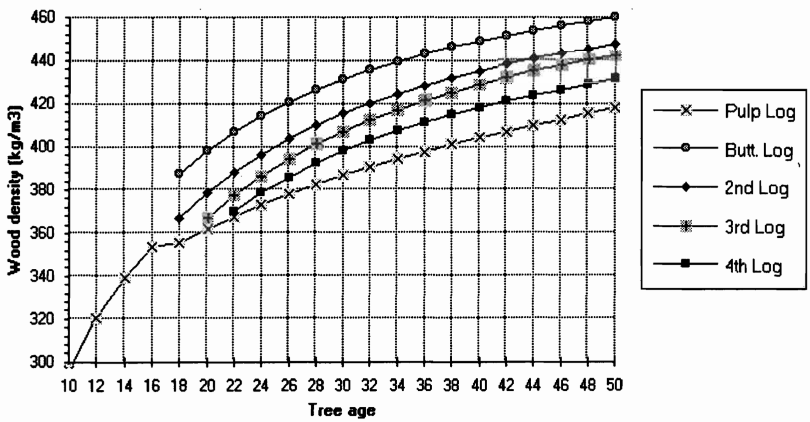


FIG. 12–Tree component (individual log) wood density model.

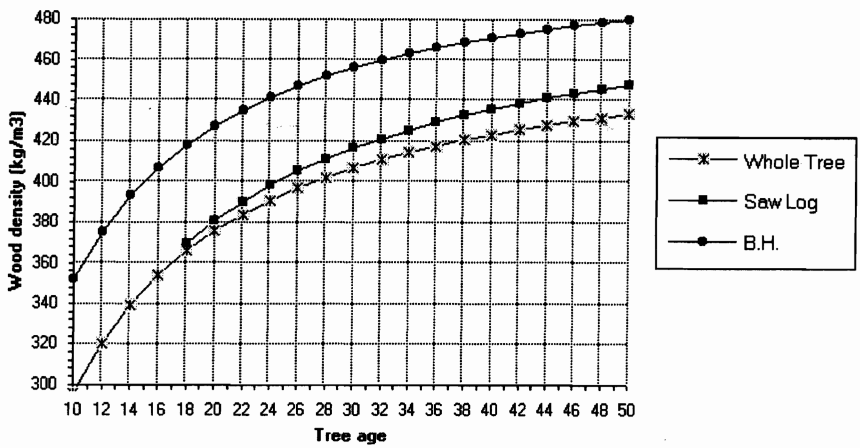


FIG. 13–Tree component (whole tree, sawlog, and breast height outerwood) density model by stand age.

average wood density (adjusted for section width) for each five-ring section at a particular sample height and growth period.

Large differences in wood density were observed between the sampling positions (Fig. 14a), with a minimum average value of 329 kg/m^3 at 32.7 m (rings 0–5) and a maximum average wood density of 459 kg/m^3 at 1.2 m (rings 40–45), a difference of 130 kg/m^3 at age 43 years. Similarly, for the 25-year-old trees (Fig. 14b) the minimum value was 332 kg/m^3 and the maximum value 435 kg/m^3, a difference of just over 100 kg/m^3. The data indicated similar overall vertical trends in the two stands (Table 4).

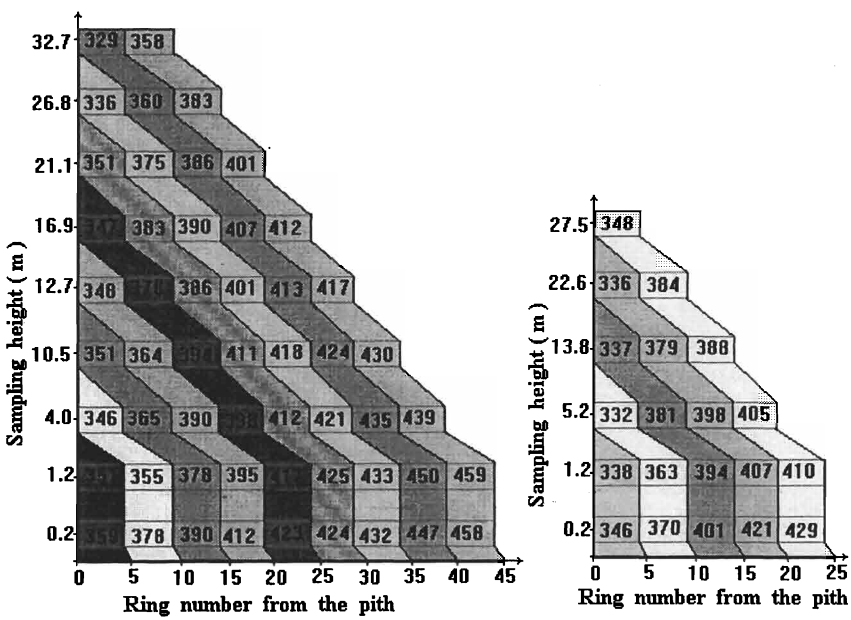
This again confirms the importance of both tree age and position in the stem.

Theoretically, a conical tree exhibiting cylindrical symmetry will have the same average trends in wood properties as those along a radius at the base of the tree. Therefore, for any

TABLE 3–Wood density data for Tree No.15-01 (42 years old, Wairoa Forest)

Disc data			Wood density (kg/m³) at							
Height (m)	Diam. (mm)	No. of rings	0–5	6–10	11–15	16–20	21–25 rings from pith	26–30	31–35	36–40
0.15	94	40	319	353	375	394	397	419	430	445
1.22	78	37	329	357	366	392	401	402	415	410
3.04	75	35	311	361	388	380	393	405	406	
8.69	64	32	344	379	400	403	414	409	392	
12.3	61	30	360	380	400	409	418	407		
16.9	54	27	370	379	403	416	425	404		
20.4	48	25	359	385	413	430	423			
26.8	36	20	355	391	427	436				
33.2	24	15	367	412	437					
38.4	16	10	351	380						
41.5	5	5	317							
Mean			344	378	402	408	410	408	417	445

Note: Wood density = resin-extracted



(a) (b)

FIG. 14–Wood density variation within stems of *Pinus radiata* (a) 43 years old, (b) 25 years old. Least-squares means were derived from 13 and 15 trees respectively, adjusted for average widths of 5-year (five-ring) sections.

piece of wood within the tree, its volume-weighted average property can be expressed in terms of:

ring number (**RN**), diameter (**D**), stem height (**H**), and tree age (**AGE**) (Fig. 15).

TABLE 4—Comparison of wood density in two stands

Tree age	Weighted density (kg/m^3) by disc height					
	0.2 m	1.2 m	4.0~5.2 m	12.7~13.8 m	21.1~22.6 m	26.8~27.5 m
25	393	382	379	368	360	348
43	415	410	400	395	378	360

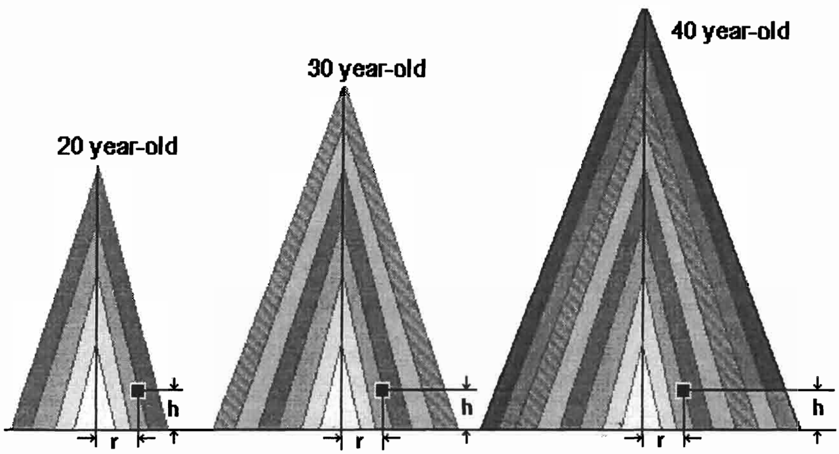


FIG. 15—Relationship between wood density and position within the tree.

According to Equation [1], the overall model for average wood basic density within the tree should be given by the multivariate non-linear formula:

$$\mathbf{WD} = \mathbf{F\,(RN,H)} + \varepsilon$$
$$= \frac{\alpha}{[\beta + e^{-\phi}]} + \varepsilon \qquad [10]$$

There α, β, ϕ are undetermined model parameters,

and $\alpha = \mathbf{f_1(H)}$

$\beta = \mathbf{f_2(H)}$

$\mathbf{f} = \mathbf{f_3(RN,H)}$, $\mathbf{f_1} \sim \mathbf{f_3}$ are undetermined functions,

F is the multi variate non-linear function,

e is random error and **e** ~ $N(0,s^2)$ normal distribution.

In the model [Equation 10], parameters can be calculated with the improved Gauss-Newton iterative method (Tian *et al.* 1995).

Generally, construction of the multivariate non-linear model includes three steps: (1) analysis of sample data (Fig. 16a), (2) local two-element model building (Fig. 16b), (3) multivariate model building (Fig. 16c).

Final solution:

$$\boldsymbol{WD} = \frac{\boldsymbol{a_0 - a_1 \cdot H}}{\mathbf{1} + (a_2 - a_3 \cdot H) \cdot e^{-RN \cdot (a_4 + a_5 \cdot H)}} \qquad [11]$$

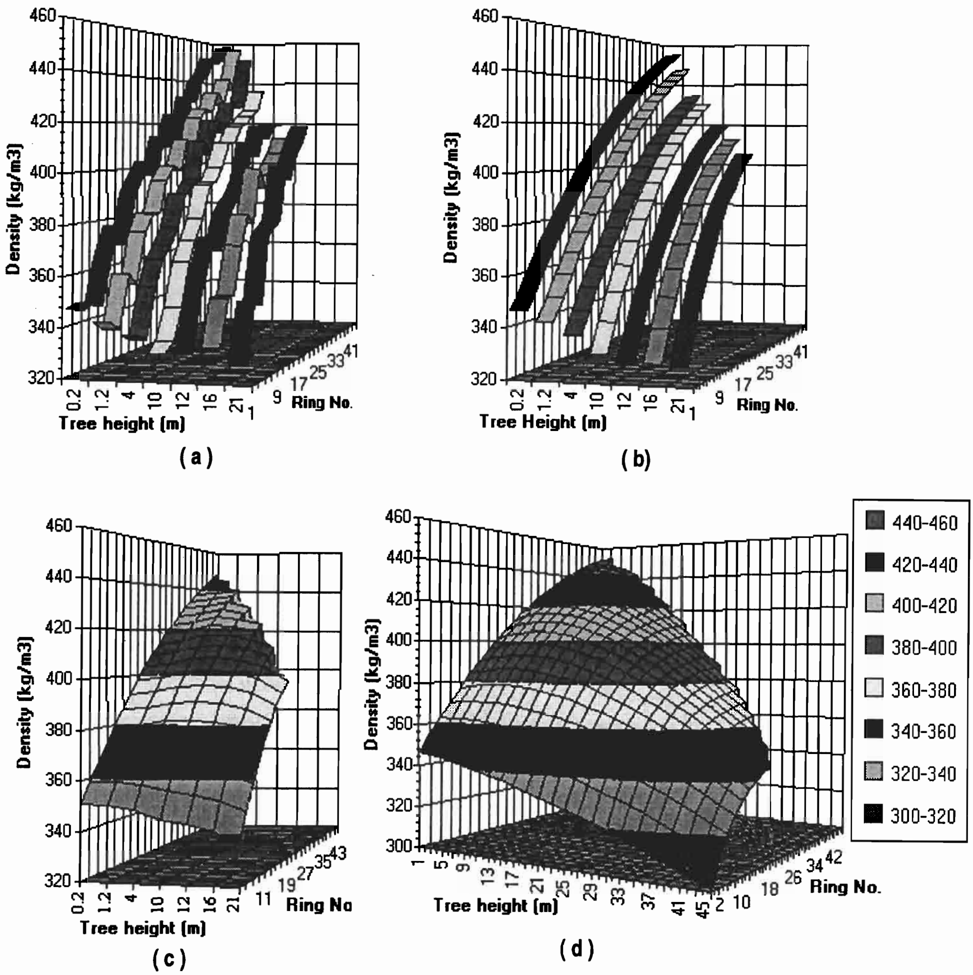


FIG. 16—Comparison between sample data, local models, and overall model.

(a) Variation of density with ring number and stem height for a 43-year-old stand in 3-D line mode.

(b) A group of local models for the same 43-year-old stand, showing variation of basic density from rings 1 to 43 at different stem heights (0.2~21 m) in 3-D line mode.

(c) An overall model for the same 43-year-old stand, showing variation of basic density from rings 1 to 43 at different stem heights (1~21 m) using 3-D surface mode.

(d) The overall model, showing variation of basic density from rings 1 to 45 at different stem heights (1~45 m) using 3-D surface mode.

where a_0, a_1, ..., a_5 are parameters. The parameters of the model [Equation 11] were estimated from 25- and 43-year-old stands in Wairoa Forest using non-linear regression. They were $a_0 = 482.89$, $a_1 = 2.97$, $a_2 = 0.42$, $a_3 = 0.0046$, $a_4 = 0.040$, $a_5 = 0.0024$.

This analysis was performed using the proc NLIN from SYSTAT. The main results of the statistical analysis are presented in Table 5.

TABLE 5–Statistical analysis for wood density (WD) by the proc NLIN of SYSTAT

Source	Sum of squares	D.F.	Mean square
Regression	0.441076E + 09	5	0.110269E + 09
Residual	5654077.314	966	2292.813
Total	0.446730E + 09	971	
Corrected	0.118787E + 08	970	
Raw R^2	(1 – Residual/Total) = 0.9170		
Corrected R^2	(1 – Residual/Corrected) = 0.7280		

Residuals were examined for the effects of ring number from the pith and height in the tree on wood density (WD) for this model.

Residuals = 100* (measured WD – predicted WD) / measured WD

The residuals, when represented *v.* ring number and height in the stem, were randomly distributed and unbiased (Fig. 17 and 18) indicating that the regression coefficients are highly significant.

The overall pattern of variation in wood density in a 45-year-old stand can be calculated by this model (Table 6).

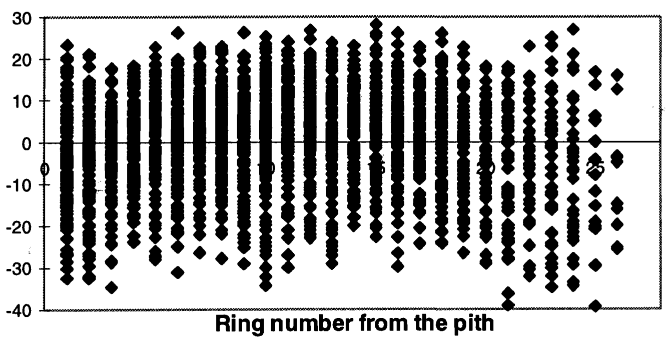


FIG. 17–Residuals between the measured and predicted wood density (%) *v.* ring number from the pith.

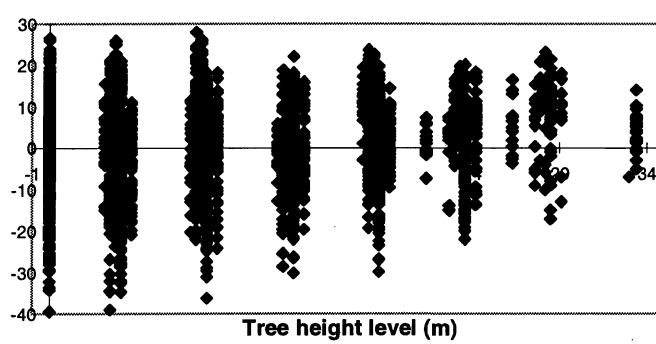


FIG. 18–Residuals between the measured and predicted wood density (%) *v.* height in the tree.

Generally, the model [Equation 11] predicts density within ±8 kg/m^3. The results (Table 6) show that the model fits the trees from the 43-year-old stand quite well, and the

TABLE 6–Wood density(kg/m^3) within trees, calculated using the model [Equation 11]

Sample height (m)	Ring number from pith								
	0–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	40–45
32.7	324	349							
26.8	331	357	375						
21.1	337	363	382	395					
16.9	341	367	386	400	411				
12.7	344	369	388	404	415	424			
10.5	345	370	389	405	417	426	433		
4.0	349	370	389	404	417	428	437	444	
1.2	350	370	387	401	415	426	435	443	450
0.2	350	369	386	400	413	425	433	442	449

model is able to account for a significant part of the variation in wood density of different stands.

Application of the Model

Having determined that average tree wood density patterns are largely predictable, based on tree age and location, the model can be used to:

(1) Predict log and tree densities from small non-destructive breast height samples

(2) Predict future log wood density levels from field samples.

Modelling Within-tree Density Patterns

The average distribution of wood density within the whole tree at different tree ages was calculated by using model [11] (Fig. 19) since it has been established that there is a strong pattern of density development, characteristic of the species and dependent on tree age and height.

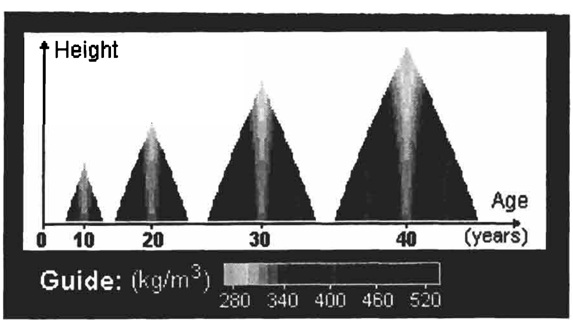


FIG. 19–Within-tree basic density distribution by decade.

Prediction of Tree Density and Tree Component Densities

The model [Equation 11] is capable of accurately calculating the average wood density values of any section of wood within the tree. Given that accurate estimates of the outerwood density can be obtained efficiently from breast height increment cores (5-mm diameter), the model can be used to predict average whole-tree densities and tree component densities from age and outerwood basic density (Fig. 20).

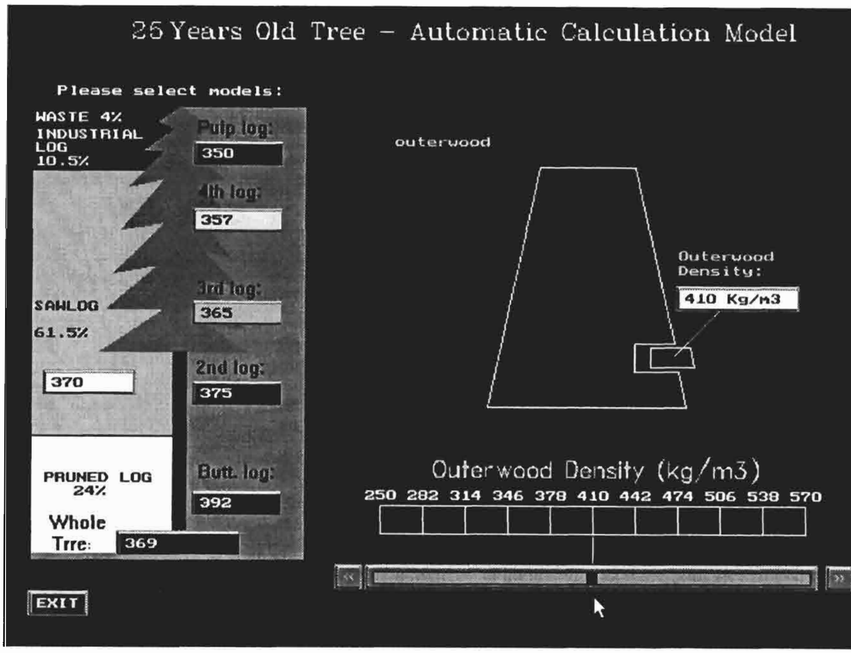


FIG. 20–Prediction of whole-tree and tree component densities.

To validate the model, the average breast-height outerwood data (wood density of the outer five growth rings at 1.4 m height) from the 25 year-old stand (410 kg/m^3) was used to predict whole-tree densities and tree component densities (Fig. 20). The predicted values were compared with measured data and the results showed that the predicted values were very close to the actual measured data (Table 7).

Of more general interest is the ability to predict whole-tree and tree component densities from increment core outerwood basic density and to predict density into the future, e.g., to the anticipated rotation age.

TABLE 7–Comparison of predicted and measured wood density values in a 25-year-old stand.

Tree component	Predicted values (kg/m^3)	Measured values (kg/m^3)	Difference (kg/m^3)
Butt log	392	393	1
Second log	375	379	4
Third log	365	368	3
Fourth log	357	N/A	
All sawlogs	370	373	3
Pulplogs	350	356	6
Whole tree	369	371	2

reast height outerwood density = 410 kg/m^3 at 25 years

The model was used with the above sample data (outerwood density 410 kg/m^3 at 25 years) to predict tree and log densities 18 years into the future (Fig. 21). The predicted values were compared with those measured in the 43-year-old sample trees. The results (Table 8) show that the predicted and measured wood density values are extremely close.

The model performs very well to predict both current and future wood density (Tables 7 and 8).

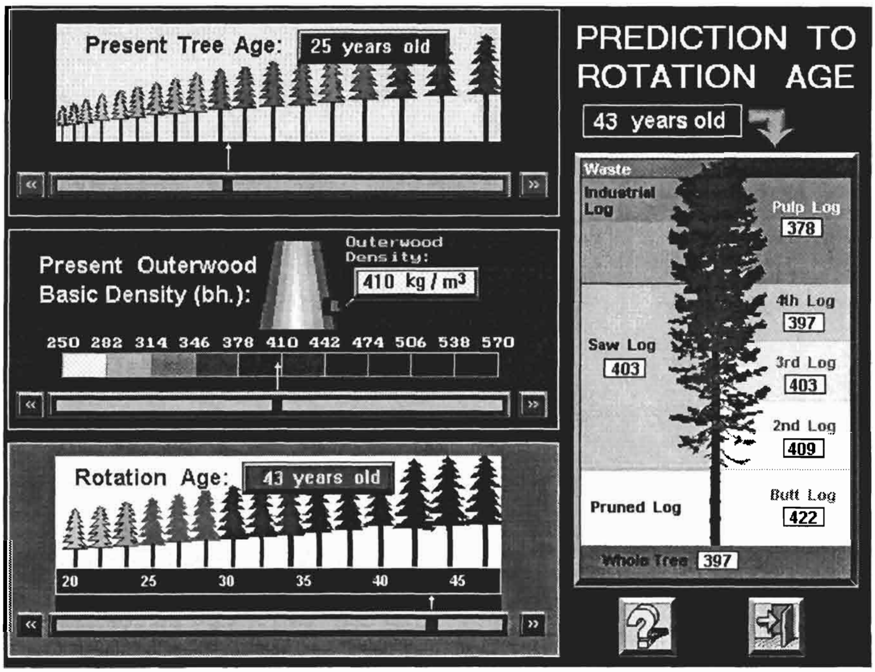


FIG. 21–Prediction of tree density and tree component densities using the model.

TABLE 8–Comparison between predicted values and measured values

Whole-tree and tree component densities at 43 years	Predicted values (kg/m^3)	Measured values (kg/m^3)	Difference (kg/m^3)
Butt log	422	413	9
Second log	409	400	9
Third log	403	391	12
Fourth log	392	389	3
All sawlogs	403	398	5
Pulplogs	378	372	4
Whole tree	397	389	8

Breast height outerwood density = 410 kg/m^3 at 25 years

DISCUSSION AND CONCLUSION

Sawing studies with *P. radiata* logs have consistently shown that wood density is a critical property for production of structural lumber (Cown *et al.* 1986). It is therefore important to understand the sources of variation in this wood property and to anticipate any changes.

Mathematical techniques have been applied to describe the patterns of variation in wood density of *P. radiata* in New Zealand, and a general model for average within-tree wood basic density was constructed. The model reveals the variation of wood density within the tree in detail, based on a very large dataset collected over several decades. The key variables have been confirmed as stand location (region) and tree age.

Prediction of tree component density from samples conveniently collected from the breast height position has been used before (Cown *et al.* 1984; Cown 1992) but the use of a model creates the possibility of incorporating wood property data into routine field assessment procedures. The wood density of the whole tree or parts of the stem (sawlogs, pulplogs) at a given age can then be projected forward to the anticipated rotation length, allowing foresters to influence felling and/or allocation decisions using wood property information.

Further refinement of the model could include linking the data to individual tree or stand models so that the influence of silvicultural decisions can be more accurately predicted for different growing conditions.

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