PO Box 1127
Rotorua 3040
Ph: + 64 7 921 1883
Fax: + 64 7 921 1020
Email: info@ffr.co.nz
Web: www.ffr.co.nz

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Wood Density Models

Authors:
D Cown, M Riddell, M Kimberley, D Pont

Research Provider:
Scion

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EXECUTIVE SUMMARY

The importance of wood density as a wood quality determinant in radiata pine is indisputable due to its strong impact on wood stiffness and strength and various pulping characteristics (yield and fibre quality), and has been the subject of a lot of research over the past 50 years or so.

The major reason for interest in wood density from growers and processors has been its strong contribution to timber stiffness and pulping characteristics, and more recently to carbon sequestration.

The drivers of density have been shown to be climate, site, genotype and silviculture, and “Density Zones” have been recognised in New Zealand for some decades. Increased emphasis on the possible impacts of climate change and carbon sequestration has resulted in a need for better prediction tools of wood density.

The requirements for forest growers are seen as:

1. Predictions of stand mean density values for bare land (improvements in identifying Density Zones). Suggested accuracy of average log predictions ± 30kg/m^3.
2. Prediction from breast height data (e.g. PSP pre-harvest inventory) forward in time. Suggested accuracy of average log predictions ± 20kg/m^3.
3. Ability to predict log densities at different heights from outerwood breast height core densities to assist with log segregation strategies ± 20kg/m^3.

This report firstly describes the density models available for radiata pine in New Zealand. The second part of the report is a validation of these models covering only the third of the above requirements. A separate report has recently been prepared for the RPBC covering the second requirement (Mark Kimberley *pers comm*), of predicting future density from young stems.

New Zealand research has already demonstrated that non-destructive sampling with 5-mm BH increment cores is a very convenient and valid approach for determining not only density of the butt log, but for providing estimates further up the stem. Several models are now in existence to predict outerwood, log, and stem densities, and have been widely used by industry here and in Australia. In several studies density has been shown to be a very good predictor of wood stiffness in mature stands.

WQI in recent years has packaged some of its wood quality research into algorithms for forest managers and made them available to YTGen and Forecaster.

FFR as a relatively new organisation must decide which of the available models should be recommended to shareholders, and how new density data should be handled to assist members.

The objective of this report is to review the currently available wood density models in YTGen and Atlas Forecaster (a Scion model and a WQI model). There was some overlap in the data used to construct the models, and also slight differences in approach and the variables considered, due to varying objectives. The models were tested with several historic datasets to examine their robustness in accounting for differences in log densities (in 5-m height classes) between crop ages, locations, genotypes and spacing treatments.

A series of studies were used for testing the abilities of the Scion and WQI models for predicting log densities by height class from breast-height outerwood density. The studies covered a range of sites (mainly in the Central North Island), stand age, stocking, and genotypes. Overall, both models performed reasonably well, with stand mean residuals (actual density – predicted density) for each log height almost always within ± 40 kg/m^3. For the Scion model, stand mean residuals were generally within ± 15 kg/m^3, except for extreme stockings (100 sph at Tikitere and 890 sph at Tarawera Valley where the model in both cases under-predicted by 20-30 kg/m^3). The WQI model also performed satisfactorily but generally had greater absolute residuals with a tendency to under-predict.

A proliferation of density models based on different datasets will be confusing for users, and is undesirable. Not all models have the potential to be updated into the future. In particular, the WQI models (now in Forecaster) may not be further enhanced.

A suggested procedure is:

- Grow stand to harvest age using growth model
- Assign stand average BH outerwood density from
    - Bare land estimate (site and climate)
    - PSP or mid-rotation data
- Distribute BH density values between individual stems
- Assign log values from BH outerwood density using validated relationships.

To achieve the best results for FFR shareholders (some of whom are not WQI members), it will be desirable to combine all existing wood density data into a single National Database, along with new data resulting from future studies. This would allow FFR to focus on gaps in the data and update functions regularly.

INTRODUCTION

Yield forecasting systems are available which produce estimates of volume, length and piece count by log grades, but do not handle wood properties well.

Wood density has long been recognised as a critical variable relating to both stiffness and stability of solid wood products and yield of oven-dry fibre from pulplogs and residues. Early work on radiata pine, particularly by Harris (1965), established that there are significant regional trends which would certainly affect the value of radiata pine pulp, logs and lumber. Subsequently wood density became a major focus of the work at FRI – effects of site, silviculture, tree age and genetics. The major drivers were:

1. The known correlation with lumber stiffness
2. Ease of non-destructive measurement (5-mm increment cores from BH)
3. Ability to predict log and stem values from the BH cores into the future.

The early work resulted in some "models", both informal (Cown and McConchie, 1982; Cown *et al.,* 1991) and formal, for example STANDQUA (Tian *et al.,* 1996). While density and stiffness remain major criteria related to stand value, at least for unpruned logs, the methods of assessment have changed with the advent of acoustic tools which assess the speed of sound in stems and logs. When WQI was set up in 2003, wood density was seen as remaining a key property, and studies included both density and acoustic measures. Some additional models were produced for shareholders.

Even more recently, carbon sequestration issues have led to at least one additional wood density model, allowing prediction of annual mass accumulation in stands in response to site and silviculture (Beets *et al.,* 2004).

It was decided within FFR to review the available "wood density models" before committing to a specific FFR approach for the next few years, which will be dependent on the perceived uses.

Basic wood density (oven-dry weight/unit volume) is a critical wood property as it directly influences all major end uses (lumber, panels, pulp, carbon/biomass). Although density is an easy attribute to measure on small or large samples, it is a complex characteristic affected by several factors, such as tree age, environment, management practices, and genotype, and is thus subject to much variation, within and between forests.

A confounding factor is the presence of resin in the wood, and the development of heartwood. Sapwood has a consistently low resin content (1-2% of dry weight). When heartwood starts to form from the centre of the stem after about 10-12 years, the moisture content drops to around 45% and the resin content increases significantly. This affects the "unextracted" density. The additional chemical content does not influence the mechanical properties, and scientists often use the "extracted" density[1] to examine relationships. Density values from unextracted samples, such as discs, will have inflated values for the heartwood zone, which can confound the basic density values.

Early Models

From the 1960s to the 1980s, two large density surveys were carried out in New Zealand to document variation across the country (Harris, 1965; Cown and McConchie, 1982a; Cown *et al.,* 1991). Analyses of factors influencing wood density revealed that apart from stand age, site and climate were very important. Outerwood density was found to be quite strongly correlated with site location (6.5 kg/m^3 for every 1^0 latitude and 7 kg/m^3 for every 100m increase in altitude). Additional improvements in predictions were achieved by including specific site factors such as soil nutrients

[1] Resin extraction can be done on small samples using a solvent such as methanol.

and rainfall (Table 1). Thousands of stems were included in the databases at the time and more data have been accumulated since.

Table 1: Relationships from Wood Properties Survey (Cown *et al.*, 1991)

Corewood density = 536 – 3.6 × latitude – 0.04 × altitude ($r^2 = 0.31$)

Outerwood density = 737 – 6.5 × latitude – 0.07 × altitude ($r^2 = 0.52$)

Better predictions can be made if some additional site data are available. The results of regression analyses using mean annual temperature, annual rainfall, and soil N, P, and pH were as follows:

Corewood density = 8.6 × temp. – 15.7 × pH – 31.5 × N – 0.12 × P + 371 ($r^2 = 0.46$)

Outerwood density = 12.0 × temp. + 0.02 × rain. – 6.0 × pH – 50.8 × N – 0.19 × P + 344 ($r^2 = 0.63$)

It was clear throughout the study that outerwood values were not only more variable but also more closely related to environmental variables than corewood densities.

Wood density varies in a predictable manner within stems:

- Increasing by growth ring number from the pith
- Decreasing up the stem

Individual stem values also vary according to:

- Radial growth and height patterns
- Geographic region (more rapid increase in warmer areas).

These trends are summarised in Figure 1.

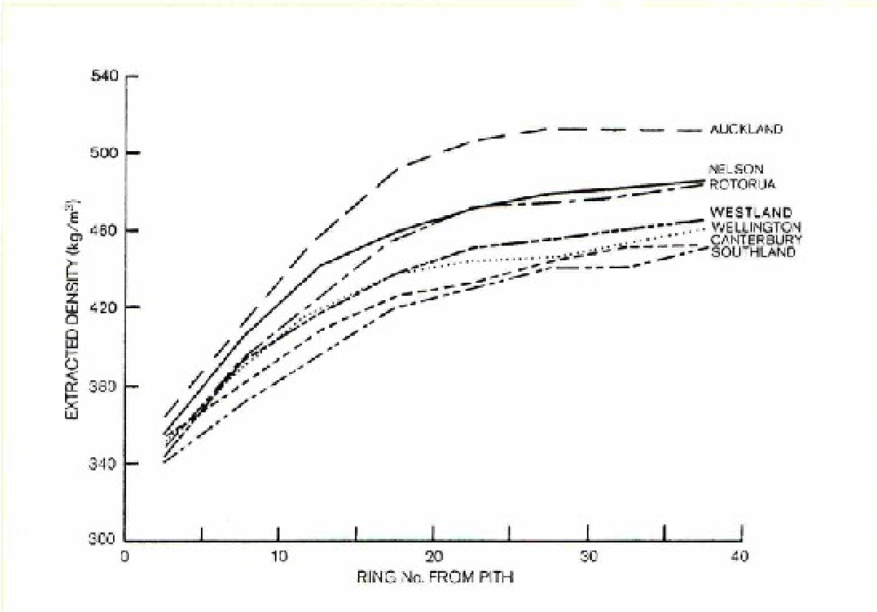

Figure 1: Regional Density Trends[2] (from Cown *et al.,* 1991).

Relationships between stem wood density components (logs) have been described for radiata pine, and predictions made from BH increment core samples (Cown, 1974; Cown and McConchie, 1982b; Cown *et al.,* 1991; Tian *et al.,* 1996, 1997) with the objective of using non-destructive increment cores to describe resource quality. All early predictive relationships were based on unextracted density from 5-mm BH increment cores (2/stem) and 5-ring density blocks removed from 500 discs at 5-m intervals up stems to a top diameter of 100 m. Average stem, sawlog and pulplog values were presented by region and stand age (Cown *et al.* 1991), and these have been confirmed in later studies to be robust.

Wood Density Algorithm and STANDQUA (Cown et al 1996+)

The trends established in FRI research (particularly the NZ Wood Density Survey – 1977-1983 - Cown and McConchie, 1982b; Cown *et al.,* 1991) were incorporated into a “Density Algorithm” for use in predicting stem density components within stands and into the future (Tian and Cown, 1996, 1997). The model (the FRI Density Algorithm) was developed originally by Dave Cown and Damian Mulvena of Scion (FRI), and later modified at various times by Xin Tian, Mark Kimberley and Rod Ball (Tian *et al.* 1996). Trends are shown in Figure 2.

[2] Unextracted density is used to illustrate the juvenile wood patterns.

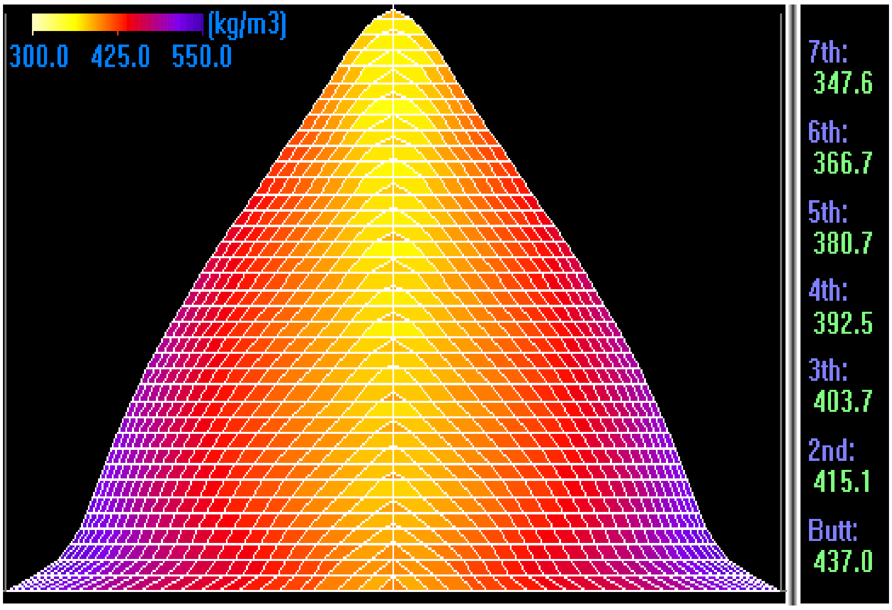

Figure 2: Within-stem Density Trends (from Tian and Cown 1996)

The objectives were to:

1. Predict log densities by height class from BH outerwood density measurements.
2. "Grow" outerwood density from measurement age into the future.

Data were sourced from the National Log and Timber Database (outerwood – 2 cores/tree - and disc densities for over 300 m sites). A very large number of trees and sites were represented, and five stems were felled at each of 35 sites for detailed within-tree density measures. Originally 5-m log values only were predicted, but a modification suggested by industry in the 1990s (Value Recovery Programme) involved the estimation of variable-length logs. The algorithm was based on a set of regression equations to predict density in terms of tree age, growth ring number from the pith and height in the stem (Tian *et al.* 1996, 1997). The generic relationship is shown in Table 2.

Table 2: Non-linear density equation to predict ring density

$$WD = \frac{a_0 - a_1 \cdot H}{1 + (a_2 - a_3 \cdot H) \cdot e^{-R \cdot (a_4 + a_5 \cdot H)}}$$

Where WD is the wood basic density (kg/m3);
H is the height from the butt (m);
R is ring number from the pith;
a_0, a_1,...,a_5 are parameters. The parameters of model [1] were estimated from a 25-year-old stand in Wairoa Forest using non-linear regreetion (Tian, Cown and McConchie 1994.). They are : a_0=482.89, a_1=2.97, a_2=0.42, a_3=0.0046, a_4=0.040, a_5=0.00244. The residual standard error is 1.1856 and the multiple correlation coefficient is 0.91.

Validation of the original model showed results to be randomly distributed and unbiased, and generally predicted ring density to within +/- 8 kg/m^3 and log densities to +/- 5 kg/m^3 (Tian *et al.*, 1996). A validation of the predictive ability of the model (18 years into the future) showed average log densities were predicted to +/- 10 kg/m^3. The Value Recovery version of the model allowed predictions for non-standard logs (i.e. varying length). This was deemed highly satisfactory.

Over the years the Density Algorithm has been customised to particular forests and regions for commercial clients (Mangatu and Ruatoria – 1999; Hikurangi Forest Farms – 2001; Green Triangle – 2004; Tasmania – 2005; Pöyry Forest Industry - 2006). It has been recommended that for new applications, a sample of between 15 and 30 stems should be used for calibration of the prediction equations. Predictions are generally within 1 or 2% of actual densities (Roper *et al.*, 2004).

The Density Algorithm has been used in conjunction with a generic growth model (together called STANDQUA)

Recent developments

There have been several new "radiata pine wood density models" developed over recent years, to enable prediction of site and tree component densities (stems, sawlogs, pulpwood, biomass), from non-destructive BH samples. All have used different data and have somewhat different objectives.

All models described below predict stem and/or log values from a wood density measurement taken at breast height. The original FRI model was based on data from 5-mm increment cores (2/stem) collected during the course of extensive wood quality studies. Originally 5-ring increment samples were used, but over time a pragmatic decision was made to use 50-mm samples instead to streamline the laboratory assessments. The model was used for stands over 15 years of age, but it was suggested that if younger trees were considered, the samples should revert to 5-ring groups to maintain biological robustness (avoid over-predicting large diameter stems). The intended use was to predict stand averages, but it was recognised that stem and log distributions were significant.

Using BH density values as a reference, models can be used to predict breast height density at rings or at ages different from the actual measurement age (e.g., weighted average BH density or BH outerwood density at some future age). Another approach is to use predictive functions to first calculate the BH density, then stem components. Some also predict within-stem density variation. Unextracted densities are almost universally used in these models, except where SilviScan data have been used in development.

Pont Prototype Density Model

A model of basic density (and ring width) was developed as part of an MSc thesis (Pont 2003). The model is based on the concepts of Larson and Pressler regarding the influence of crown / foliage on wood development, on the basis that this could produce a model of within-stem variation in density and make the model responsive to influences on crown structure (genetics, environment, silviculture).

The model is designed to be linked to crown models (such as the branch growth model, BLOSSIM), requiring information about the amounts and locations of foliage within the crown in order to predict density variation along annual growth layers. Model development was carried out using detailed measurements from just one tree. To date, only a small amount of testing and further development has been carried out using data from a few trees on three sites. The model fitted, using variables D_{fia} (average distance to foliage above stem position at age *a*) and W_{f0a} (total foliage mass above stem base at age *a*) is:

$$\rho_{ia} = 452.3\left(\frac{D_{fia}}{W_{f0a}}\right)^{0.108}$$

During model development the predictive ability of the variable D_{tia} (distance to the tip of the tree) was shown to be almost as good as D_{fia}. It is interesting to note that the revised density model of Rawley (2007 - see below) added a term for distance from the tip. The model's functional form is simple and amenable to further testing and calibration, but the requirement for crown information (crown foliage mass, average distance to foliage or distance to tip) as inputs, limits the availability of suitable data sets. Future development could be carried out using existing and future data collected for further development of BLOSSIM (Pont *et al.*, 2002).

WQI Model(s)

The "WQI Models" were developed because the Scion Density Algorithm was not made freely available to WQI in recognition of its historic nature and the significant extent of its underpinning database.

Model from WQI Benchmarking Study (Mason and Dzierzon, 2007)

Wood density data obtained from discs from the felled trees (10 each from 17 sites across NZ) were used to investigate relationships between site characteristics, growth rate and wood density within stems. Both SilviScan radial trends (air-dry extracted density) and 5-ring block sectors (unextracted basic density) were used.

Using the 5-ring block data, it was concluded that density is dependent on both temperature and ring width (Table 3a). This is in line with previous findings (Cown *et al.*, 1991). Slightly different functions were found to fit the air-dry extracted SilviScan density data (Table 3b).

Table 3a: Basic Density Functions from WQI Benchmarking Study (Mason and Dzierzon, 2007)

Variable	λ	Estimate	Std. Error	t-Value	Pr > |t|
Intercept		417.21	8.4059	49.63	<.0001
Mean temperature, specific year (°C)		2.4296	0.6810	3.57	0.0004
Ring width (mm)	0.7	-3.5291	0.3136	-11.25	<.0001
Transformed ring number*Mean Tmp	0.05	2.3010	0.06942	33.15	<.0001
Height of disc (m)	-0.3	-19.4112	1.5630	-12.42	<.0001

Table 3b: Air-dry Density Functions from WQI Benchmarking Study (Mason and Dzierzon, 2007)

Table 17 – Model of density from SilviScan analyses. The r^2 of the model was 0.44.

Variable	λ	Estimate	Std. Error	t-Value	Pr > |t|
Intercept		185.16	25.8127	7.17	<.0001
Winter temperature (° C)		34.7193	2.4624	14.10	<.0001
Ring width (mm)	0.3	23.7738	4.0477	5.87	<.0001
Transfolmed ring number	0.8	4.0777	0.2683	15.20	<.0001
Height of disc (m)	-1.1	-3.8474	0.6554	-5.87	<.0001
Log of foliar Mg		38.5908	2.9525	13.07	<.0001
Winter T * transformed ring width		-4.2033	0.3948	-10.65	<.0001

The functions were intended to be used in conjunction with ring-level models.

Other WQI Models for Density Prediction

(Rawley, 2006, 2007; Woolons and Manley, 2008)

This system consists of several model components which perform the following functions:

1. Predict outerwood density from site and stand variables.
2. Predict disc density at a specified height from BH disc density.
3. Predict BH disc density from BH outerwood density.
4. Estimate the distribution of individual tree BH outerwood density from a stand mean BH outerwood density.
5. Predict BH outerwood density at a specified age from BH outerwood density at some other age.

The original version (Rawley, 2006) was achieved using data from WQI and "other contributed sets" (CHH and Fletcher Challenge Forests) – a total of 31 sites. The output is a series of equations, suitable for implementation in YTGen or Atlas Forecaster (Rawley, 2006). Some validation work was carried out by WQI, and a revised version was produced using more WQI and CHH data (Rawley, 2007).

1. Predict outerwood density from site and stand variables (INT 15 - Woollons and Manley, 2008).

This study reported on the prediction of BH outerwood density (50 mm) from site and stand variables (age, altitude, latitude, diameter and height). It used data from large CNI databases as well as WQI data (Benchmarking Study and other sources), covering ages from 15 to 40 years.

A predictive function was derived (Table 4).

Table 4: Predictive Function for Outerwood Density (Woolons and Manley, 2008)

$$PDENSITY = \beta_0 + \beta_1\sqrt{T} + \beta_2 ALT + \beta_3 NORTH + \beta_4 \log(FATNESS) + \beta_5 SANDS \qquad (2)$$

Where:

PDENSITY = Predicted outerwood BH density
T = Stand Age (Yrs)
ALT = Average Altitude
NORTH = NZMG Northing (m)
FATNESS = Stand Average DBH/Mean Top Height
SANDS = Dummy Variable = 1 for sand forests, = 0 for others

Relative Contributions:

Variable	Partial R^2
ALTITUDE	**0.395**
AGE	**0.242**
NORTHING	**0.036**
SANDS (DUMMY) *	**0.017**
FATNESS	**0.015**
	0.705

***** - The dummy "sands" variable adds 26 kg/m^3.

This model is claimed to be useful for planning purposes, with estimated 95% confidence limits of +/- 37 kg/m^3. This is an approach very similar to that used by Cown *et al.*, (1991), but based on a smaller dataset (mainly Central North Island), and using "fatness" ("slenderness") as an additional variable.

2. Predict disc density at a specified height from BH density (Rawley, 2006, 2007)

In this model, the position in the stem is defined in terms of relative cross-sectional area – the ratio of the disc area to disc area at BH.

A model of the form shown in Tables 5a and 5b was fitted using non-linear least squares with disc data.

The original model was used across ages from 7 to 37 years, with a range of BH disc density from 250 to 500 kg/m^3, with plausible results. The residual standard error was 15.7 kg/m^3. Absolute mean residuals were less than 4 kg/m^3 in validation studies. However, there was a site effect which was not explained by the model. The original model seemed to over-predict for predictions over 400 kg/m^3 and within 10 m of the total tree height. The new model (using new data from other regions, particularly the South Island) performed better, with no obvious site effects. The mean residual value was 1.6 kg/m^3 – but with a significant unexplained site effect.

Table 5a: Non-linear density equation to predict disc density

$$density_h = density_{bh} + (a + b * density_{bh} + d * age) * (area_h / area_{bh} - 1) \quad (2)$$

$density_h$	disk density at height h
$density_{bh}$	disk density at breast height
$area_h$	disk cross-sectional area inside bark at height h
$area_{bh}$	disk cross-sectional area inside bark at breast height

Table 5b: Revised non-linear density equation to predict disc density

Equation 1 Prediction of disk density

$$\log(bd_x) = a + b * (1 - \exp(c * x)) + d * dbh * x + (e/(\text{dbh} + \text{h})) * \exp(\text{f} * (1 - \text{x})) + \text{g} * \log(\text{bhobd}) + \varepsilon_t + \varepsilon$$

Where:

bd_x	Unextracted disk density at position x (kg/m^3)
x	Distance from tip of tree / height of tree (unitless 0-1)
dbh	Diameter of tree at 1.4m from ground, overbark (mm)
$bhobd$	Stand mean breast height outer wood basic density (kg/m^3)
ε_t	Error term attributable to differences in basic density among trees
ε	Error term attributable to lack of fit of model within a tree

<u>Comment</u>: Absolute disc height was considered to be unsatisfactory for inclusion in the model, as it could lead to potential extrapolation problems (i.e., no upper bound).

3. Predict disc density from BH outerwood density (Rawley, 2006, 2007)

This model uses outerwood density (50 mm cores) to predict BH density (245 trees from 23 sites – 7 to 25 years) – Table 6.

Table 6 Non-linear density equation to predict disc density

$$density_{bh} = a + b * bhobd \quad (3)$$

$density_h$	disk density at height h (kg/m^3)
$bhobd$	breast height outer wood basic density (kg/^{m3})
a,b	parameters to be estimated

The mean difference between predicted and actual disc densities was 1.6 kg/m^3. However, there were still site effects which were not explained by the model.

4. Estimate the distribution of individual tree BH outerwood density from a stand mean BH outerwood density

Variation in density between individual stems within a site is the dominant source of variation (Cown and van Wyk, 2004). The WQI data showed that the overall coefficient of variation for a disc having 400 kg/m^3 density was around 5.5% without taking account of a small negative DBH effect, and 5.7% accounting for DBH, i.e. individual stems will vary between about 360 and 450 kg/m^3. Age was not a significant factor affecting the variation in outerwood density (Cown *et al.,* 1991; Rawley, 2007).

5. Predict BH outerwood density at a specified age from BH outerwood density at some other age

The WQI data were modelled as in Table 7, with results in Figure 3. Note similarity with the Scion data (Figure 1a).

Table 7: Non-linear density equation to predict disc density

$$bhobd = (a + d * altitude + f * nzmg.northing) * (1 - c * e^{-b*age}) \quad (6)$$

In this form, the altitude and northing parameters are used to reduce variation in the data and improve the estimate of parameters b and c. They are not used in the final predictive or growth model.

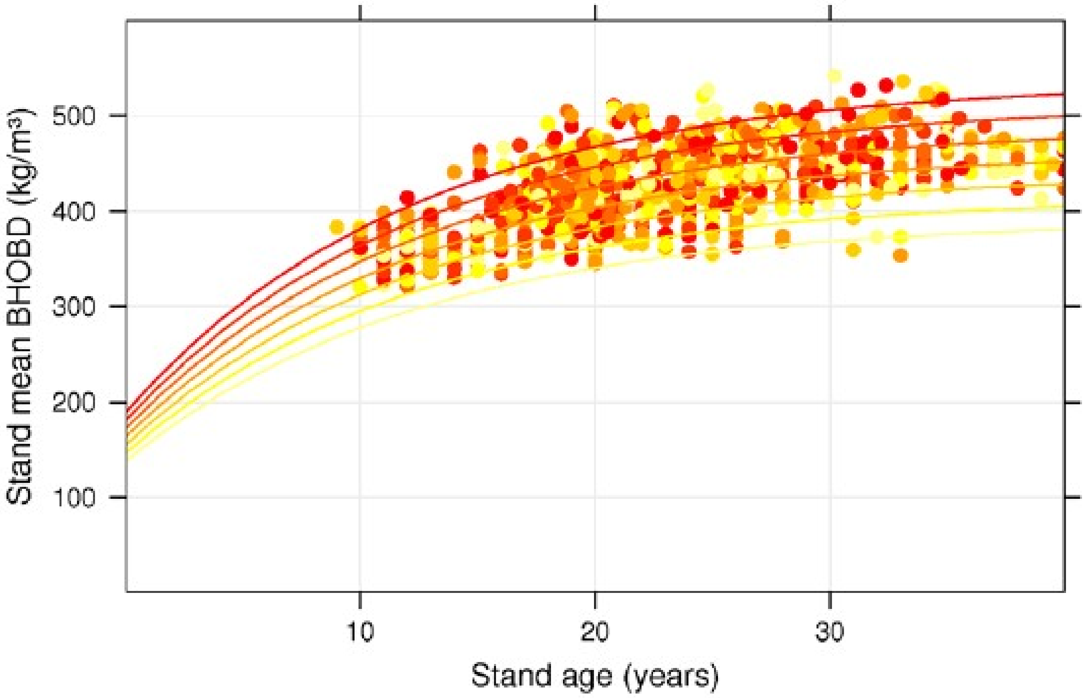

Figure 3: WQI Model: Regional Density Trends (Rawley, 2006).

The implementation to predict harvest age wood density was envisioned as:

1. "Grow" the stand tree data and outerwood density to the proposed harvest age. (Data used ranged from ages 7 to 25 years. **<u>Caution</u>:** It is not recommended to use 50 mm core for prediction from very young ages.)

2. Assign an outerwood value to each stem at harvest age according to a normal distribution.
3. Estimate BH disc density for each stem.
4. "Buck" stems using an existing bucking algorithm, taper and volume functions, and estimate the basic density for each stem component.

The final model (Rawley, 2007) gives better predictions for the top logs and incorporates a small DBH effect (negative).

Other WQI Models

RES 15 (Beets *et al,* 2004)

The WQI Benchmarking study (GF14 1978 material across 17 sites) was used to examine climatic and site factors influencing wood density. A number of regression models were derived to explain outerwood density (2 cores/tree). Site mean outerwood density was predicted from site mean annual temperature, a soil nitrogen fertility index, and foliage K/Mg balance, with R^2 values of models involving these variables generally accounting for approximately 95% of the variation in site mean outerwood density, nationally (Table 8). No other soil or foliage variables were found to play additional roles. Using the model, the site mean outerwood density in stands of any age but with the same genetic base ("850" series) can be predicted at maturity from climate and site data with confidence (PLE = 5%), even without trees.

Table 8: Outerwood Density prediction (Beets *et al.*, 2004)

Table 2. Outerwood density regression models based on a selection of climate, soil, and foliage variables, and associated R^2 and adjusted R^2 (adjusted for sample size). The model coefficients (X1-X3) and standard errors of these coefficients (in brackets) are also shown. Without a model, the 95% CI for mean density was 79 kg/m^3 with a PLE of 19%.

Model	X1	X2	X3	R^2	R^2 adj.	95% CI (±kg/m^3)	PLE (95%)	Intercept	X1	X2	X3
1	Temp			0.79	0.82	39	9.5	225 (25)	15.9 (2.1)		
2	Temp	0-5cm C/N		0.89	0.92	29	7.1	126 (33)	18.0 (1.6)	4.0 (1.1)	
3	Temp	0-5cm C/(N-0.014)	Fol K/Mg	0.96	0.99	19	4.6	188 (23)	15.4 (1.0)	3.4 (0.7)	-4.3 (1.4)
4	Temp	0-5cm C	0-5cm N	0.90	0.93	30	7.3	240 (27)	14.7 (1.8)	12.6 (3.5)	-278 (73)
5	Temp	0-10cm C/N		0.90	0.93	28	6.8	112 (34)	19.1 (1.7)	4.2 (1.1)	
6	Temp	0-5cm C/N	Ln(Fol. Mg)	0.96	0.99	19	4.6	216 (28)	17.3 (1.1)	4.1 (0.7)	45 (10)
7	Temp	0-5cm C/N	Fol K/Mg	0.97	1.00	16	3.9	175 (20)	17.2 (0.9)	4.0 (0.6)	-6.5 (1.1)
8	Temp	ln(Fol N)		0.85	0.87	35	8.5	274 (31)	15.5 (1.9)	-111 (50)	
9	Temp	ln(Fol N)	Ln(Fol Mg)	0.90	0.93	29	7.1	374 (44)	14.3 (1.6)	-124 (41)	42 (15)
10	Temp	Foliage C/N	Ln(Fol Mg)	0.91	0.93	29	7.1	197 (53)	14.3 (1.6)	3.6 (1.1)	42 (15)
11	Latitude	Altitude		0.79	0.82	41	10.0	810 (56)	9.3 (1.4)	0.057 (0.025)	

"While the model predictions will be biased if the genetic base has changed, corrections should be possible. For example, if genotypes of inherently high wood density were planted at a range of sites, the model would be expected to consistently underestimate density at these sites. However, it should be possible to develop a valid adjustment factor determined specifically for each seedlot, family, or clone, and "correct" the model predictions, without having to re-derive the model." - Beets *et al*., (2004).

Beets/Kimberley/McKinley Model

This report describes a density model for predicting the mean density of annual stem wood growth sheaths for any stand with suitable input data. This model was developed for use in predicting carbon sequestration in radiata pine stands as a function of site mean annual temperature, soil nitrogen fertility, ring age, and stocking. Its main purpose is to predict the wood density of 'growth sheaths', i.e., the wood laid down in an annual growth increment (Beets *et al*., 2007).

The wood density model has been incorporated in a carbon modelling system (C_Change) to facilitate the prediction of carbon stocks and changes in New Zealand's exotic plantation forest estate. C_Change requires the gross and net total stem volume increment under bark, which can be predicted using empirical growth models, such as the 300 Index Model. The latter model can be calibrated directly using individual plot measurement data. Secondly, it requires the mean density of the stem wood growth sheath laid down annually. Wood density varies considerably in *P. radiata* both within and between trees, and between stands, and it is therefore important to account for this variation when calculating the mean density of the growth sheath.

The model is based on measurements of mean outerwood basic density at breast height of 30 trees per stand from a single seedlot established at 17 sites located throughout New Zealand. Soil and climate data were obtained from each site, and stem wood disks were sampled at 5-m intervals along the stem from 10 trees per stand from 15 of these sites. The database used included historic Scion information covering a wide range of sites, stand ages, and stockings (Beets, 1997; Beets *et al.,* 2001; Cown, 1974b; Cown and McConchie, 1981; Cown *et al.,* 1991). It also included the WQI benchmarking data. Previously reported breast-height basic density data from a comprehensive national survey were used to examine ring age trends from pith to bark, supplemented with data from four trials to determine the influence of tree stocking on outerwood density. The model was tested using data from an independent study of mean outerwood basic density at breast height (30–120 trees per stand) undertaken at 21 stands selected to cover a wide range in site fertility, temperature, tree stocking, and stand age.

To predict the density of annual stem wood growth sheaths, the model firstly estimates the effects of site mean annual temperature, soil nitrogen fertility, and stocking, on mean outerwood density at breast height. Secondly, the effect of ring age on annual ring density at breast height from pith to bark is taken into account. Finally, the ratio of sheath density to breast-height ring density for each ring is estimated as a function of stand age and outerwood density. The national wood density model explained 93% of the variation in outerwood density at breast height for the model development dataset, with model predictions within 0.2% of the measured values. The model explained 86% of the variation in breast-height ring density in the model validation dataset, with predictions from the model averaging 3.2% higher than the measured values. Seedlot differences in breast-height outerwood density contributed in part to the greater variability evident in the validation dataset. The modelled ratios used to predict the density of annual growth increments were not directly tested. However, analogous ratios of whole stem wood density/breast-height outerwood density were derived by site density class for stands across a range of age classes using an independent national dataset, and these were consistent with those predicted using the model.

Applying the model to predict the mean outerwood density at breast height ($D_{O,250}$) in 25-year-old stands with an average stocking of 250 stems/ha from temperature and soil C/(N – 0.014) had an R^2 of 0.93 (equation below). Standard errors of the coefficients are shown in parentheses:

$$D_{O,250} = \underset{(22)}{143} + \underset{(1.3)}{15.9}T + \underset{(0.8)}{4.1}C/(N - 0.014)$$

Additional adjustments were made for growth rate and regional density gradients to estimate the effect of site, ring age, growth rate and height in stem on the wood density of individual growth sheaths within the stem.

Validation of the model against a large independent dataset indicated that the prediction of BH density was robust (prediction error 3.2%).

The resulting model clearly demonstrated that the most significant variable affecting density is mean annual temperature (19.9%), followed by ring age (16.4%), soil C/N (8.3%) and stocking (3.8%). This would appear to be the most comprehensive model available for predicting site, silviculture and stand age effects on wood density.

Recent studies in Australia (Raymond and Joe, 2007) suggested that in the region sampled (NSW), thinning had no discernible effect on density, and outerwood values were only poorly predicted from juvenile wood density (rings 1-10). This is contrary to NZ experience and may be because of the small geographic area sampled and the similarity between stand treatments.

A comparison of NZ models is given in Table 9.

Table 9: Comparison of Density Models

Criterion	Scion Models – Wood Density Algorithm and STANDQUA	Pont Prototype Model	WQI Density Model(s)	Beets/Kimberley/McKinley Model
Created	1990's	2003	2006 revised 2007	2007
Purpose	• Predict site density • Predict density forward in time • Account for silviculture • Predict log densities • Predict impacts on solid wood and pulp products	• Predict density variation between and within trees • Predict density through time • Account for silviculture • Predict impacts on solid wood and pulp products	• Predict site density • Predict density forward in time • Account for silviculture • Predict log densities • Predict impacts on solid wood and pulp products	• Predict site density from environmental variables • Predict density forward in time • Account for silviculture • Can be calibrated using outerwood density measurement • Predict density by ring and height • Predict density of annual stem growth sheath • Predict log density when combined with taper function
Datasets	Comprehensive historic data from density surveys, silviculture/genetics trials and sawing studies.	A single tree, extended to a few trees from 2 sites.	Mainly WQI data, supplemented by CNI company outerwood data.	Comprehensive historic data from density surveys as summarised in FRI Bulletin No. 50, supplemented by stocking trials and WQI Benchmarking Study data.
Validation	Has been validated in many trials and commercial studies and customised to local needs.	The model is in development.	Has been validated against WQI data and deemed satisfactory after additional data collected.	Outerwood density validated against independent data from 21 stands and two stocking trials. Ratio of whole stem to outerwood density validated against tabulated data from FRI Bulletin No. 50.
Future Use in Modelling	Could be used as input to future FFR models as more data become available. Can be customised to regions or new genotypes.	Development could be continued. Inputs could be simplified. Hybrid with other (stand-level) density models to obtain within and between stem variations.	Unlikely to be extended beyond the life of WQI.	Could be used as input to future FFR models as more data become available. Can be customised to regions or new genotypes.

METHODS

From the various models previously described, it was decided to compare the two which are currently available in Atlas Forecaster – the Scion Density Model and the WQI Model. Nine datasets (Table 10) were used to compare density predictions using the Scion Algorithm with predictions using the WQI INT11 Algorithm. All nine studies were sited in the Central North Island forests, and selected on the basis of comprehensive wood density data (BH core values and actual log densities from discs) with some solid basis for providing comparative results (e.g. variable spacing, age, genotype). Where stem information required for validation (such as total height) was not available, it was estimated using the height and diameter of the highest disc and a taper function.

The nine validation study datasets allow examination of different aspects:

- Effect of crop age (Kaingaroa Forest). The age of harvest was the main variable of interest. The original objective was to provide material of different ages (21 years, 26 years, and 30 years) for detailed sawing and pulping processing studies. They involved a large numbers of trees (140 trees in total for the four studies combined), and because they were carried through to sawing and board grading assessments, very good tree branching information was also collected. There were some differences in site (different stands and altitudes within Kaingaroa Forest) and seed source (the 21-year study was a long internode progeny test).
- Effect of spacing (Tikitere – agroforestry, and Tarawera Forests). These studies were originally carried out to quantify the effects of spacing on wood quality. Harvest ages were very different for these two studies – 19 years for Tikitere and 35 years for Tarawera.
- Impact of genotype (Eleven clones and Value Recovery Studies). Originally, these were wood quality studies (Cown *et al.,* 2002) linked to processing studies – kraft pulping in the former case, and sawing and peeling studies in the latter (Beauregard *et al.*, 1999, 2002; Harding and Orange, 1998). Harvest ages were very different – 16 years for Eleven clones, 27 years for VR1 and 28 years for VR2 respectively.

Comparison of Models

The Scion Algorithm was provided by Rod Ball (Feb 2009). The model is intended to provide stand mean predictions and produce log average results at the stand level. The intention of the model developers was to provide a new set of model coefficients, as required, for any changes in forest site (soils, altitude, latitude), silvicultural regime, and seed source. That is, the model is intended to be calibrated for new applications.

Using the Scion Algorithm (inclusive of coefficients from a calibration across multiple sites) predictions were made for the first four 5-m logs (butt, 2^{nd}, 3^{rd}, 4^{th}). The model is a simple linear model with two predictors – tree age and outerwood basic density (two opposite 50-mm outerwood cores), and with coefficients that are specific to each of the logs butt to 4^{th}.

The WQI INT 11 model was specified in WQI Report No. INT 11 (September 2007). The model form and coefficients are confidential to WQI.

The WQI model makes prediction of disc basic density at all height positions up the tree. Three predictors are used – diameter at breast height (outside bark), outerwood basic density, and ratio of distance of the disc from tip of tree to attained tree height. The predicted log densities are obtained by summing predicted disc densities within each log. The intention of the WQI model is that one model is applicable to a range of sites and silvicultural regimes. The model is intended to be used at a stand level with a random effects added to simulate between-tree variation. However in the current analysis, the random effect was not included because individual tree predictions were required.

The main difference in the Scion and WQI algorithms is that the Scion algorithm includes tree age with no tree shape information. In contrast, the WQI algorithm includes tree shape with its inclusion of diameter at breast height and attained tree height (used indirectly in disc within tree relative height position), with no tree age information. The analyses examine the differences between the actual measured log densities and the model predictions at the individual tree level.

Residual density = Measured log density – Algorithm predicted log density

Positive residual, if the algorithm predicts a lower density than measured on the log.

Negative residual, if the algorithm predicts a higher density than measured on the log.

Table 10: Studies Used For Validation

Study	Effect of Crop Age 21 years	Effect of Crop Age 25 and 26 years	Effect of Crop Age 30 years
Trial	R320/16	N/A38	N/A42
Site	Kaingaroa	Kaingaroa	Kaingaroa
Compartment	905	1013 Stand 02	1302 Stand 01.2
Slope (degrees)	3-5	5-15	5-25
Aspect	W	NE	S
Altitude (m)	552	460	380
Planting Date	1972	1965	1965 ?
Initial stocking (spha)	1250	2500	2500
Seed source	870 long internode		
Pruning	2 m at 8 years	2.2 m at 6 years 4 m at 8 years 5.8 m at 9 years	2.4 m at 3 years 4 m at 4 years 5.8 at 5 years
Thinning	600 spha at 4 years	1320 spha at 3 years 690 spha at 7 years 350 spha at 10 years	541 spha at 5 years 275 spha at 13 years
Nominal final stocking (spha)	450 incl mortality	350	
Measured final stocking (spha)			267 – Marvl inventory
Felling date	1993	1990 and 1991	1993
Age at felling	21	25 and 26	30
Samples	10 stems Outerwood cores. Discs at 5m intervals from 5-ring density blocks.	20 stems Outerwood cores. Discs at 5m intervals from. 5-ring density blocks.	10 stems Outerwood cores. Discs at 5m intervals from. 5-ring density blocks.
Reference	McKinley *et al.* (1994)	Young *et al.* (1991, 1992)	McKinley *et al.* (1993)

Table 10: Studies Used For Validation (contd.)

Study	Efect of Spacing Tikitere 1993	Effect of Spacing Tarawera Valley Regimes	Effect of Genotype 11 Clones	Effect of Genotype Value Recovery 1 and 2
Trial	R0382a	RO955/9	R664/3	R944/2
Site	Tikitere	Tarawera Forest	Kaingaroa	Kaingaroa
Compartment	Agroforestry	54	327	1350
Slope (degrees)	0-15	3-5	4-15	3-5
Aspect	N	S	NW	SE
Altitude (m)	359	180	560	402
Planting Date	1973	1963	1976	1968
Initial stocking (spha)		340 and 577 final were 1350 890 final was 5300	800	1370
Seed source	850	Felling select	870/871 series clones – 1/0 cuttings from 4-yr- old hedges	266 series clones-1/1 cuttings from 7-yr-old trees
Pruning	6 m in lifts at 3, 6, 8 yrs	Unpruned	2 m at 6 yrs 6 m at 10 yrs	1.5 m at 4yrs 4 m at 6-7 yrs
Thinning	3, 6, 8 yrs	Thinned to nominal final stockings at 12 m tree height	400 spha at 9 yrs	700 spha at 6-7 yrs 350 spha at 13 yrs
Final stocking (spha)	100 200 400 thinned to stockings	340 577 890 pre-harvest measurement	400	350
Felling date	1973	1998	1992	VR1 1995 VR2 1997
Age at felling	19	35	16	27 (VR1) 28 (VR2)
Samples	31 stems Outerwood cores. Discs at 5m intervals from. 5-ring density blocks.	10 stems from each of 4 spacings. Outerwood cores. Discs at 5m intervals. 5-ring density blocks.	Two stems from each of 11 clones. Discs from 5m intervals. 5-ring density blocks.	4 stems from each of 10 clones. Outerwood cores and discs at 5m intervals (VR1) and 5, 20m (VR2). 5-ring density blocks.
Reference	McKinley *et al.* (1993)	McKinley *et al.* (2000)	Lausberg and Donaldson (1994)	McKinley *et al.* (1996); Harding and Orange, (1998); Cown *et al.* (2004)

RESULTS

Effect of Crop Age Studies

This trial was carried out over a number of years. Results of the validation are shown in Tables 11 and 12.

Table 11: Effect of Age Studies – Model Residuals – study / crop age means

Algorithm	Study Age (yr.)	Residual log 1 density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	21	-12.7	-10.3	-3.7	-3.5
	25	-11.4	-12.0	-4.7	-1.1
	26	-3.7	-2.4	5.9	12.3
	30	-2.4	3.5	8.7	13.8
	Pr>F	0.0056	0.0004	0.0044	0.0005
	n total	139	140	139	133
	All ages mean	**-8.2**	**-6.2**	**0.7**	**4.6**
WQI - INT 11	21	-4.7	-3.5	-3.1	-6.0
	25	3.9	1.2	1.9	1.5
	26	11.2	10.3	13.5	17.1
	30	18.2	22.4	23.3	23.3
	Pr>F	<0.0001	<0.0001	<0.0001	<0.0001
	n total	137	137	137	132
	All ages mean	**6.7**	**6.7**	**7.9**	**8.0**

Residuals for both models showed positive and negative values for various combinations of age and log height class (Table 8). For the stand representing 21 years (long internode breed), there were negative residuals for both algorithms and at all height levels. Overall, both models showed trends in residuals with age (Scion improving, INT deteriorating) and with height in the stem (INT less so). On average, the Scion algorithm tended to over-predict the butt and second logs while the INT algorithm under-predicted all log height classes. These trends are shown in Figures 4a, b. The large differences in model predictions between the 25 and 26-yr samples are difficult to explain, since the material is from the same stand. The highest residuals (around 20 kg/m^3) overall were observed for the WQI INT algorithm applied to the 30-yr data, however, the conclusion must be that neither model performs consistently well.

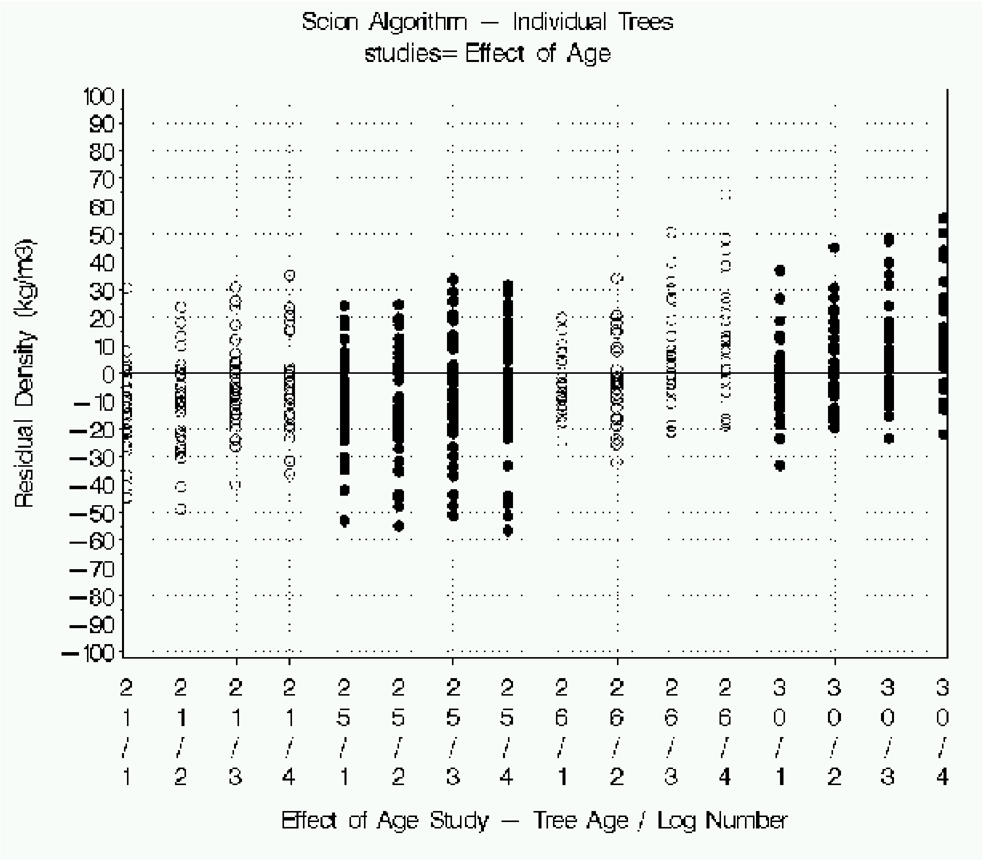

Figure 4a: Effect of Crop Age Studies - Scion Residuals

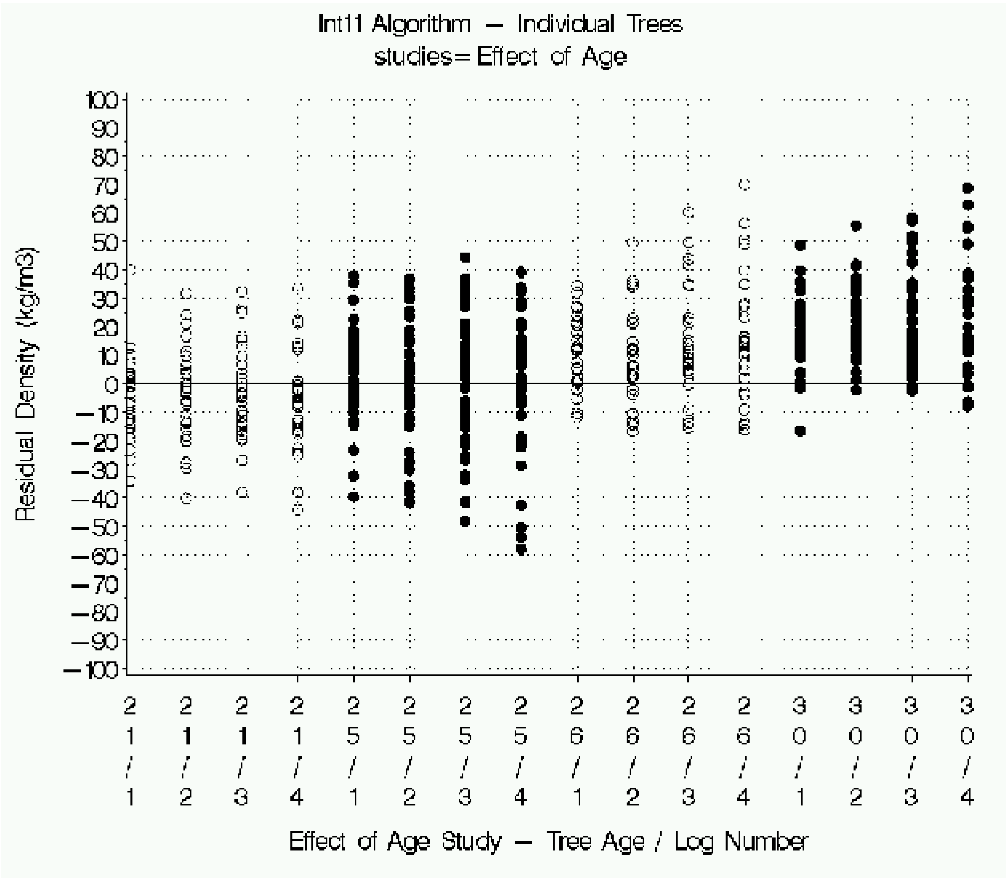

Figure 4b: Effect of Crop Age Studies – WQI INT 11 Residuals

Examination of available branch data from these studies revealed that stems with high values of Internode Index conversely had lower values of residuals (Table 12). That is, for higher Internode Index stems, the measured density is lower than predicted with the algorithm. The magnitude of the negative correlation was larger for logs further up the tree. For the 26-year and 30-year. stands, correlation coefficients were positive for both algorithms and at all log height levels. For the upper log height classes, the correlation coefficient is largest, and statistically significant. In this study, heavily branched stems tended to have a higher density than predicted by the algorithm, especially in the upper logs (Figures 5a and 5b).

Table 12: Effect of Crop Age Studies – Pearson correlation coefficients[1] (r values) between residual log densities and branching measurements

Model	Study Age (yr.)[2]	Branching measurement	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	21	Largest branch	-0.11	-0.07	-0.03	-0.14
		Branch index	-0.04	0.04	-0.04	-0.09
		Internode index	-0.16	-0.18	-0.34	**-0.53**
	26	Largest branch	0.16	0.28	**0.57**	**0.68**
		Branch index	0.14	0.22	**0.48**	**0.62**
		Internode index	-0.16	-0.20	-0.17	-0.21
	30	Largest branch	0.00	0.05	0.27	**0.40**
		Branch index	0.05	0.13	0.34	**0.45**
		Internode index	-0.02	-0.07	0.02	0.06
WQI Int 11	21	Largest branch	-0.06	-0.05	-0.02	-0.06
		Branch index	-0.01	0.03	0.05	0.00
		Internode index	-0.28	-0.26	**-0.38**	**-0.51**
	26	Largest branch	0.34	**0.37**	**0.60**	**0.70**
		Branch index	0.24	0.26	**0.48**	**0.66**
		Internode index	**-0.38**	-0.35	-0.23	-0.17
	30	Largest branch	0.11	0.05	0.26	**0.40**
		Branch index	0.12	0.10	0.32	**0.46**
		Internode index	0.02	-0.08	-0.04	-0.07

1. Correlation coefficients in bold are statistically significant at the 0.05 level.
2. No branching data was collected for the Effect of Crop Age – 25 years study

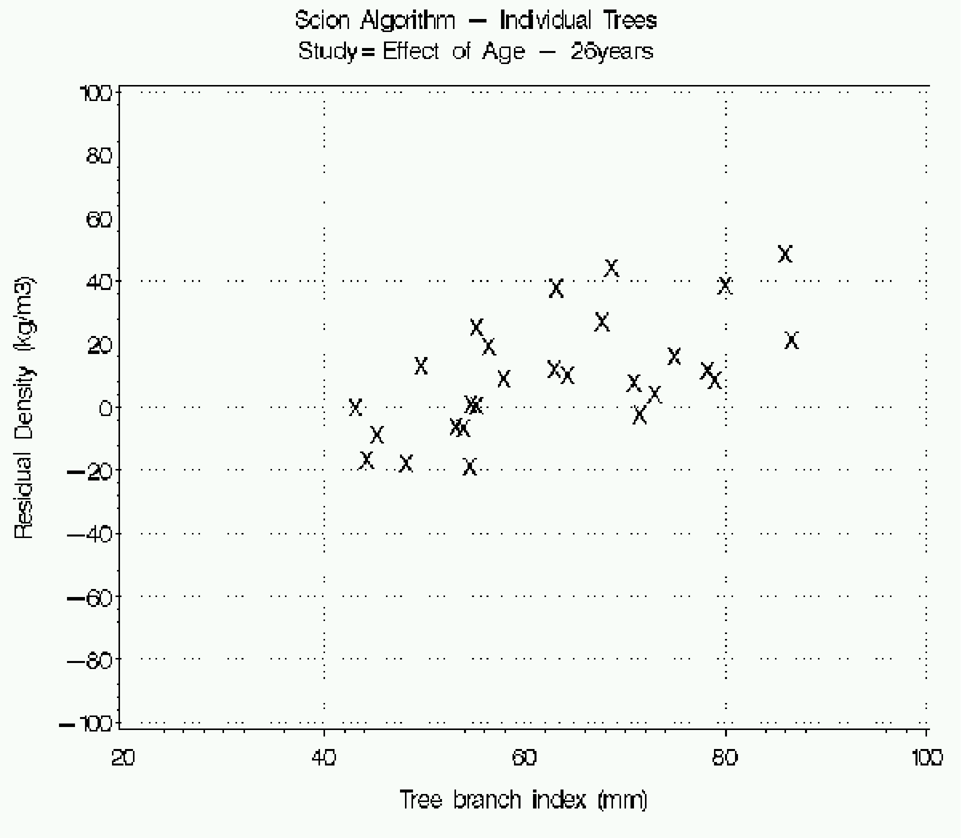

Figure 5a: Effect of Age Studies – Effect of Branch Index – Scion Data

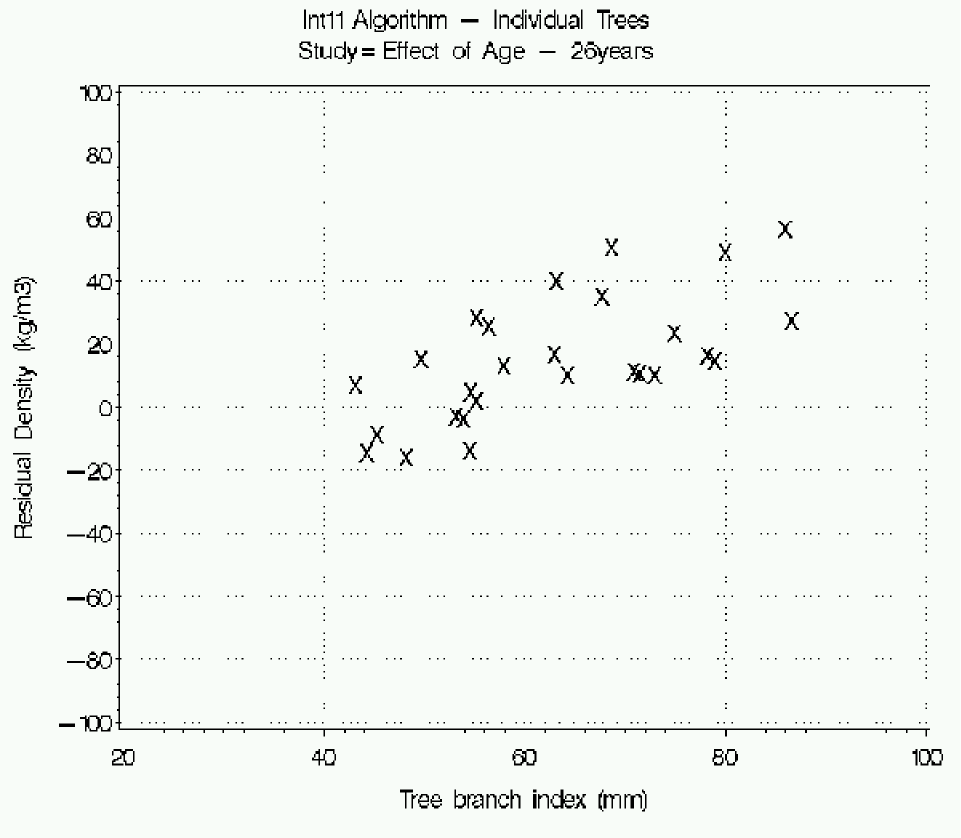

Figure 5b: Effect of Crop Age Studies – Effect of Branch Index – WQI INT 11 Data

Tikitere 1993 study (agroforestry)

Table 13 provides the mean prediction residual for each stocking rate using the two algorithms. Differences between final stocking rates in mean residuals are statistically significant for both algorithms and all logs, except for the Scion butt log. Both algorithms showed positive residuals (underprediction) for the butt log density in the 100 and 200 spha stocking for this ‘850’ seedlot. Underpredictions are more severe for the 100 spha stocking than the 200 spha stocking, and are greater for the upper logs (3rd and 4th) than the lower logs (butt and 2nd), and are slightly worse for WQI INT 11 algorithm. The absolute mean residual for the 400 spha stocking is less than 10 kg/m³ for both algorithms and all logs. Figures 6a and 6b show that individual tree residuals vary much more widely. The lower residuals for the 400 spha stockings might be because model coefficients were probably calculated from databases using predominantly final stockings in the 300-400 spha range, compared to the more extreme 100 and 200 spha on this agroforestry site.

Table 13: Tikitere 1993 Stocking Study–Model Residuals – stocking treatment means

Model	**Stocking (at thinning)**	**Residual butt log density**	**Residual log 2 density**	**Residual log 3 density**	**Residual log 4 density**
Scion	100 spha	11.1	21.2	31.9	32.6
	200 spha	3.8	2.0	13.4	17.3
	400 spha	2.1	-10.2	-4.4	-6.2
	Pr>F	0.3554	0.0002	0.0003	0.0052
	n total	36	36	36	23
	All stockings mean	**5.6**	**4.0**	**13.1**	**14.4**
WQI INT 11	100 spha	25.6	29.1	35.2	42.8
	200 spha	14.5	8.3	14.0	22.8
	400 spha	7.1	-6.9	-6.6	-6.4
	Pr>F	0.0302	<0.0001	<0.0001	0.0043
	n total	36	36	36	23
	All stockings mean	**15.5**	**9.7**	**13.6**	**19.6**

The model residuals are shown in Figures 5a, b.

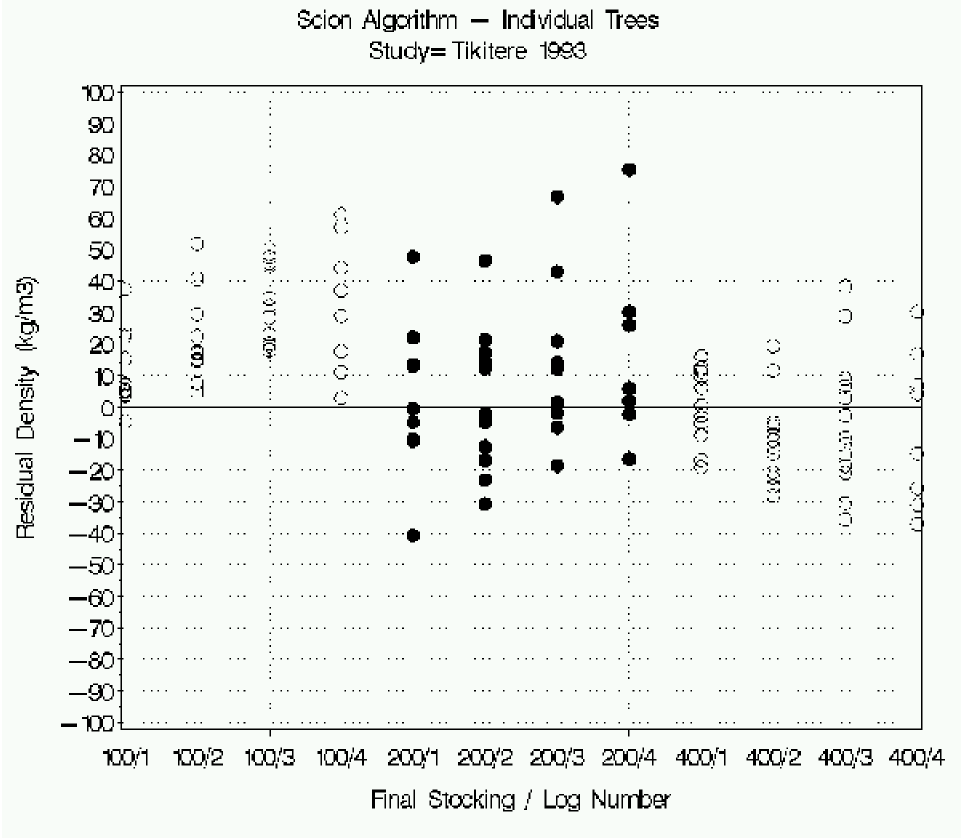

Figure 6a: Tikitere Study - Scion Residuals

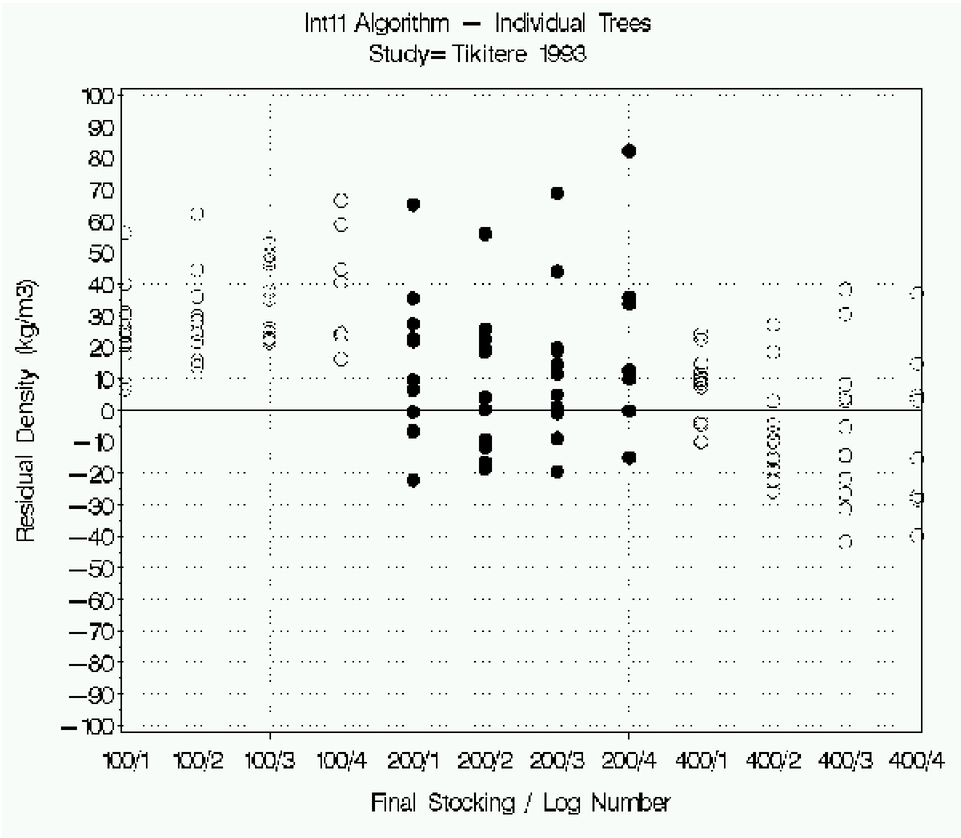

Figure 6b: Tikitere Study – WQI INT 11 Residuals

Tarawera Valley Spacing Trial

For the Tarawera Valley Spacing Trial (Felling Select – Table 14) the mean residuals for both algorithms are also mostly positive, and hence log density is under-predicted, as was found in the Tikitere analysis. Caution needs to be exercised when comparing these results across the two studies because of the large difference in harvest ages (19 years Tikitere and 35 years Tarawera).

In this case, the underprediction is much more severe for the WQI INT 11 algorithm, and this applies across all three final stocking levels. For each log height class, the residuals are all high and positive, but not significantly different from one another (0.05 level).

For the Scion Algorithm, the 890 spha log densities were underpredicted for all log height classes. This 890 spha final stocking level also had a very high initial stocking of 5300 spha which should result in less volume of low density corewood. The mean residuals are the least for the 577 spha stocking level. For the 340 spha final stocking level, the underprediction is more severe at higher log height levels, as was observed in the Tikitere study.

The residuals are shown in Figures 7a, b.

Table 14: Tarawera Valley Spacing Trial – Model Residuals – stocking treatment means

Model	Final Stocking (measured)	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	340 spha	-0.5	3.6	13.5	23.3
	577 spha	4.2	-1.0	1.4	8.3
	890 spha	17.1	20.7	23.8	24.5
	Pr>F	0.0357	0.0111	0.0307	0.1163
	n total	29	29	29	29
	All stockings mean	**7.0**	**8.1**	**13.3**	**19.1**
WQI Int 11	340 spha	27.1	30.4	35.0	36.5
	577 spha	24.0	21.7	19.7	16.9
	890 spha	31.8	40.5	40.0	32.9
	Pr>F	0.5875	0.0590	0.0579	0.0806
	n total	29	29	29	29
	All stockings mean	27.8	31.2	32.0	29.2

This validation analysis across spacing trials, would suggest:

- the models perform best when applied to conventional stocking levels, and
- the models may behave somewhat differently with different seed sources.

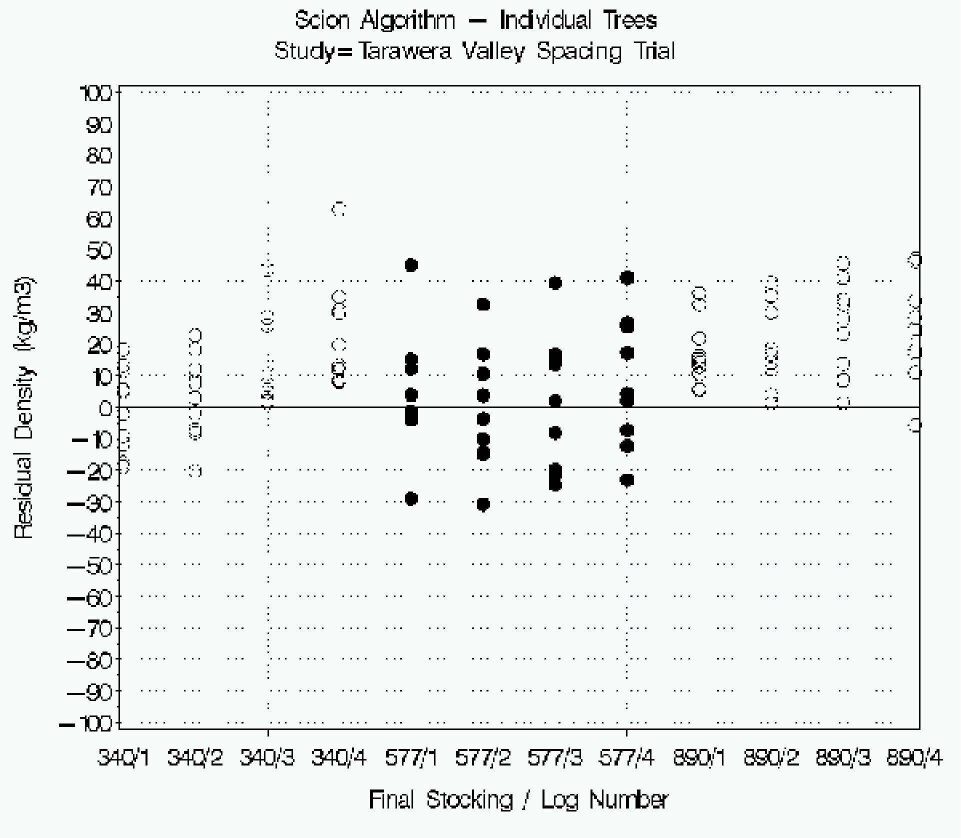

Figure 7a: Tarawera Valley Study - Scion Residuals

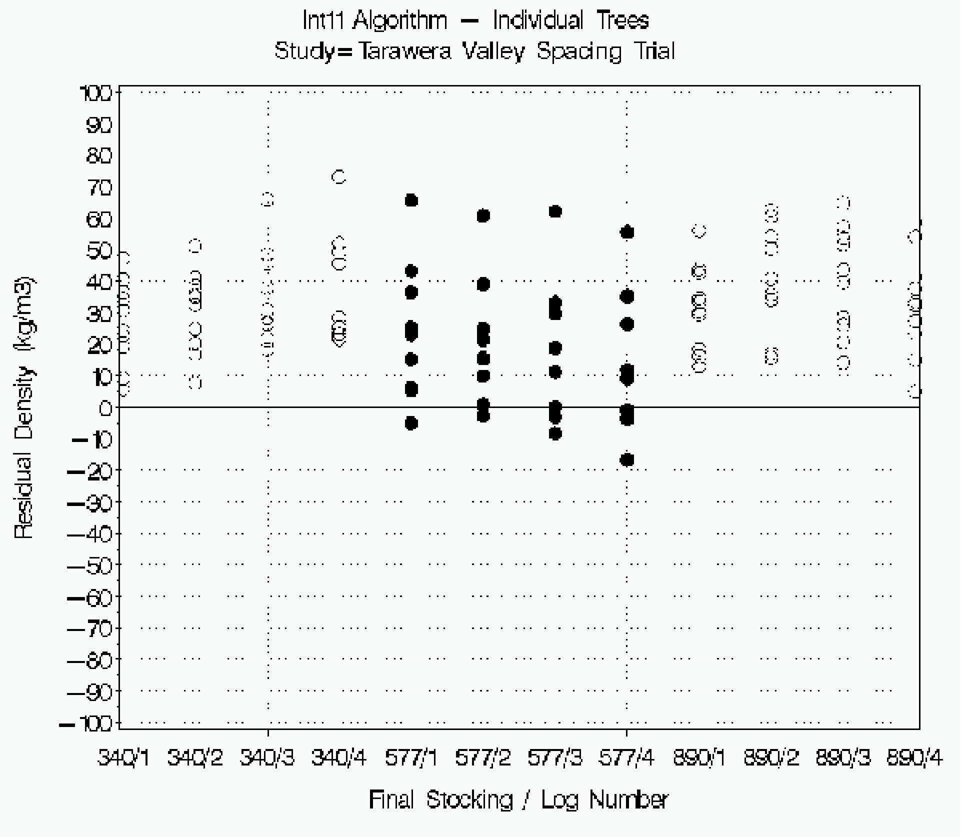

Figure 7b: Tarawera Valley Study – WQI INT 11 Residuals

Eleven Clones Study

The study clones (16 years old) were selected from a total of 120 clones which had been pre-screened to give a good range in wood density and tracheid length for the pulping studies. Stem averages for density ranged from 289 to 388 kg/m^3. BH outerwood values were calculated from disc density analyses (Lausberg and Donaldson, 1994).

Model predictions are analysed in Tables 15 and 16.

Table 15: Eleven Clones Study – Model Residuals – Clonal Means

Algorithm	Clone ID	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	126	0.8	0.5	2.8	-21.3
	13	26.1	14.8	13.8	0.1
	136	19.0	6.0	8.3	0.9
	159	13.0	12.6	10.3	-9.5
	172	30.6	22.7	16.3	-1.0
	188	12.9	2.8	-15.3	-6.2
	22	24.8	3.5	-0.3	-2.9
	27	17.1	24.8	27.8	19.0
	3	3.2	9.3	16.0	-3.7
	59	44.5	12.4	17.6	9.9
	6	1.3	-5.9	-6.3	-20.1
	Pr>F	0.0864	0.4612	0.0603	0.0032
	N total	24	24	24	21
	All clones mean	**17.5**	**10.7**	**9.9**	**-2.1**
WQI Int 11	126	-6.8	-7.0	-5.9	-18.5
	13	19.2	8.9	5.1	-0.7
	136	14.0	3.3	0.7	-3.0
	159	7.7	7.2	2.7	-6.8
	172	24.7	17.7	7.7	-3.5
	188	5.6	-1.3	-24.3	-12.1
	22	18.6	-1.9	-8.9	-4.5
	27	10.9	19.0	18.8	16.2
	3	-3.8	3.0	7.4	-2.6
	59	41.5	10.4	10.5	5.8
	6	-7.0	-13.9	-15.1	-16.2
	Pr>F	0.0270	0.3028	0.0530	0.0066
	n total	24	24	24	21
	All clones mean	**11.3**	**5.3**	**1.4**	**-2.3**

Both models behave similarly across clones – mostly under-predicting, with residuals following the same patterns. For instance, the butt log of clone 59 is significantly under-predicted by around 50 kg/m^3, the second log of clone 27 by around 20 kg/m^3, and the third log over-predicted in both cases.

This indicates that:

- Neither model is particularly well suited to predicting at this age
- Clones probably have significantly different density patterns.

Variance components for the residuals were similar for the Scion model residuals and the WQI INT 11 model residuals (Table 16). The percentage of total variation attributed to clone varied widely – from 11% for log 2 residuals to 72% for log 4 residuals. Averaging across all log height classes and the two models, the average percentage of total variation in residuals attributed to clone is 43%. The magnitude of the clonal variance component and large differences between genotypes in log residuals indicates that it is likely that wood density prediction models will need to be calibrated for which clone is being used in a clonal forestry situation, and may need to be calibrated to different seedlots for family forestry.

Table 16: Eleven Clones Study – Model Residuals Variance Components

Algorithm	Variance component	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	Clone	94	24	97	120
	Tree within clone and error	165	187	141	46
WQI INT 11	Clone	143	38	101	82
	Tree within clone and error	137	166	138	39

The model residuals are plotted in Figures 8a and b. For each clone, the differences between the two ramets (different plot marks) were fairly consistent across the log height classes. For example, the log residuals of the clone 126 tree with the filled circular plotmark were 10 to 25 density units higher than the log residuals for the clone 126 tree with the filled square plotmarks. This consistency of difference gives some indication of a small magnitude of random error in the determination method for log density values. There could however be systematic errors common to all logs of a tree. Also, for the two ramets of each clone, the pattern of change in residual with log height is usually similar (e.g. the decreasing residuals for both ramets of clones 172 and 188 as log height increases – clone 6 is an exception). The clonal differences in log height patterns of density residuals is driven by different clones having different wood density patterns radially and with height, leading to a pattern in the residuals when breast height outerwood basic density is the main predictor.

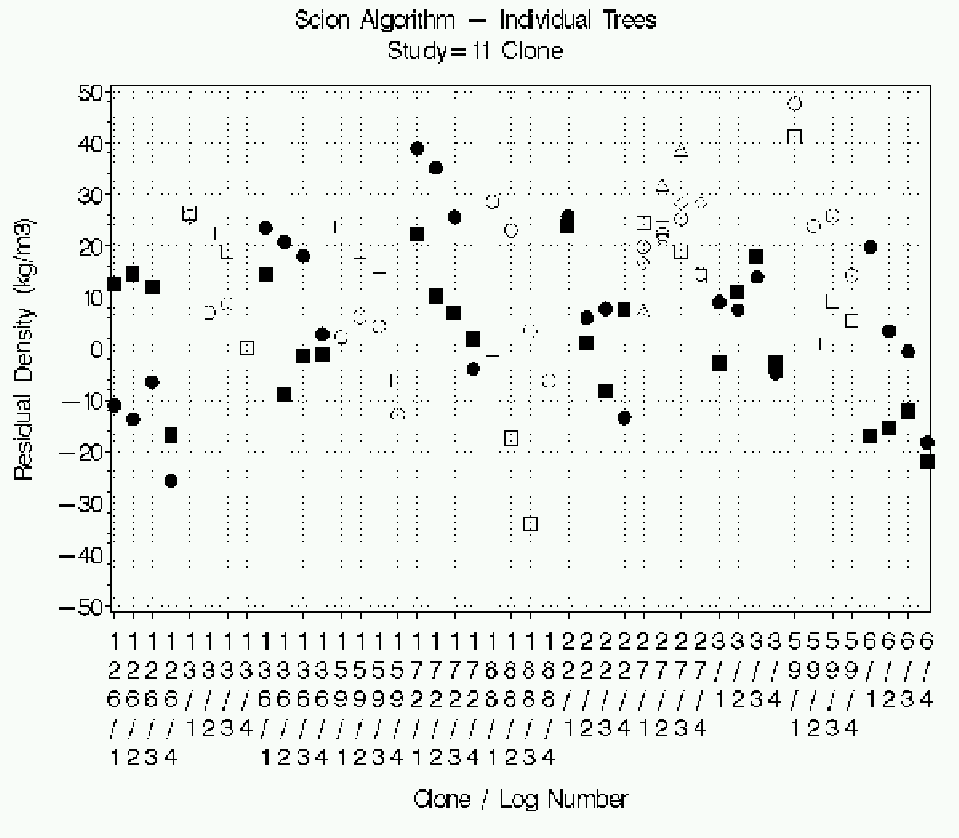

Figure 8a: 11 Clone Study – Scion Residuals

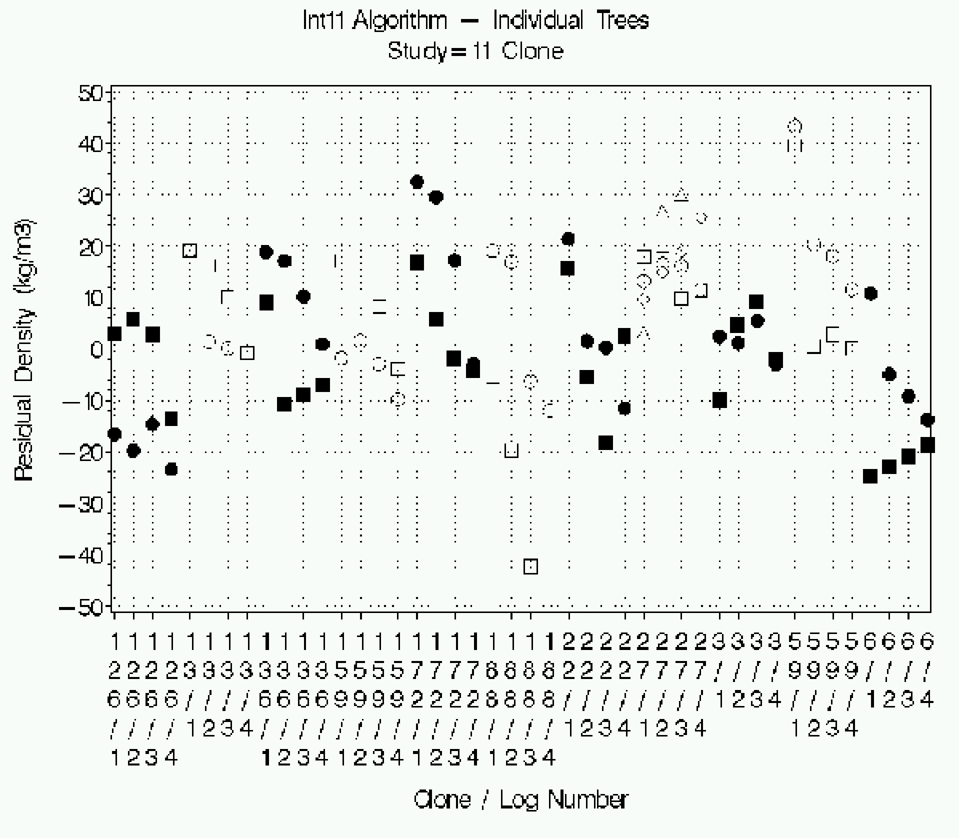

Figure 8b: 11 Clone Study – WQI INT 11 Residuals

Value Recovery Clones

The Value Recovery Clones came from Kaingaroa Forest and were harvested in successive years (2 trees from each of the same 10 clones in each year = 4 trees/clone). The objectives of the studies were somewhat different each year – logs for sawing and bolts for veneer respectively – but the sampling positions were somewhat compatible, allowing 5-m stem lengths to be assessed (VR1) or predicted (VR2). Average clonal DBH ranged from 395 to 627 mm and outerwood density from 384 to 515 kg/m^3. The two models were applied to the two datasets and the results are shown in Tables 17 – 20 and Figures. 9a, b.

Several points are apparent:

- Overall, the residuals range from -24 to +45 kg/m^3. There was a greater tendency for over-prediction in VR2 (negative values).
- For log height classes, residuals are much more consistent for VR1 (all less than +/-10 kg/m^3. For the VR2 dataset, they vary from 3.5 to 23.6 kg/m^3.
- Predictions vary quite dramatically between clones in the case of both models, indicating possible consistent genetic effects. This is very likely as other clonal studies demonstrated differences in confirmed radial and vertical trends (Donaldson *et al.,* 1996; Cown and Ball, 2004).
- The relative behaviour of clones is similar with the two models, indicating that the models react in a similar fashion to clonal changes.
- The average predictions for VR1 and VR 2 (same clones, one year difference in harvest age) are significantly different. The procedures used to calculate log densities were slightly different between VR1 and VR2, but are considered unlikely to have resulted in differences of the magnitude seen. This aspect remains a mystery.

Table 17: Value Recovery 1 Clones Study – Model Residuals – Clonal means

Algorithm	Clone ID	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	170	-14.6	-15.3	-18.0	-14.9
	210	-0.5	5.2	13.9	21.3
	238	-12.1	-9.6	-14.7	-8.2
	278	-16.9	-17.6	-16.3	-5.7
	285	-19.3	-19.2	-14.1	-23.9
	301	12.1	-6.8	-1.3	-2.9
	349	-17.2	-10.4	-10.0	-12.7
	428	10.9	3.6	14.7	21.9
	460	7.9	14.9	21.3	28.1
	95	1.5	-8.3	-3.1	10.8
	Pr>F	0.0631	0.2980	0.0079	0.0006
	N total	20	20	20	20
	All clones mean	**-4.8**	**-6.3**	**-2.7**	**1.4**
WQI Int 11	170	-3.6	-5.5	-11.2	-12.3
	210	17.9	19.9	24.7	27.4
	238	4.5	6.1	-4.0	-10.1
	278	-4.8	-6.8	-8.8	-4.7
	285	-17.9	-17.2	-12.2	-21.9
	301	13.6	0.0	3.7	-3.4
	349	-16.3	-8.5	-7.5	-8.3
	428	20.9	15.8	22.8	20.9
	460	22.3	26.3	29.9	35.5
	95	21.0	8.4	7.9	12.1
	Pr>F	0.0109	0.0664	0.0023	0.0004
	n total	20	20	20	20
	All clones mean	**5.8**	**3.8**	**4.5**	**3.5**

Table 18: Value Recovery 2 Clones Study – Model Residuals – clonal means

Algorithm	Clone ID	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	170	4.6	-4.2	7.6	13.4
	210	5.6	11.6	26.3	35.7
	238	-3.7	-3.1	4.8	17.5
	278	-3.0	4.7	18.1	13.0
	285	-5.2	-5.7	-3.7	-9.1
	301	13.6	3.3	20.8	18.9
	349	-5.4	13.6	12.4	0.8
	428	21.7	25.1	27.1	31.4
	460	3.1	12.8	23.6	37.1
	95	3.8	9.0	17.6	30.7
	Pr>F	0.1163	0.0703	0.4360	0.0211
	N total	20	20	20	20
	All clones mean	**3.5**	**6.7**	**15.5**	**19.0**
WQI Int 11	170	17.9	8.7	16.8	19.6
	210	29.2	31.2	40.3	43.5
	238	17.1	16.9	18.0	17.8
	278	13.3	19.8	28.4	16.3
	285	0.4	0.2	1.5	-1.8
	301	26.4	17.0	29.9	20.7
	349	-0.6	19.4	17.5	8.5
	428	34.5	39.8	36.8	32.3
	460	21.9	29.0	35.3	44.9
	95	25.8	28.8	31.0	34.0
	Pr>F	0.0031	0.0068	0.1888	0.0163
	n total	20	20	20	20
	All clones mean	**18.6**	**21.1**	**25.5**	**23.6**

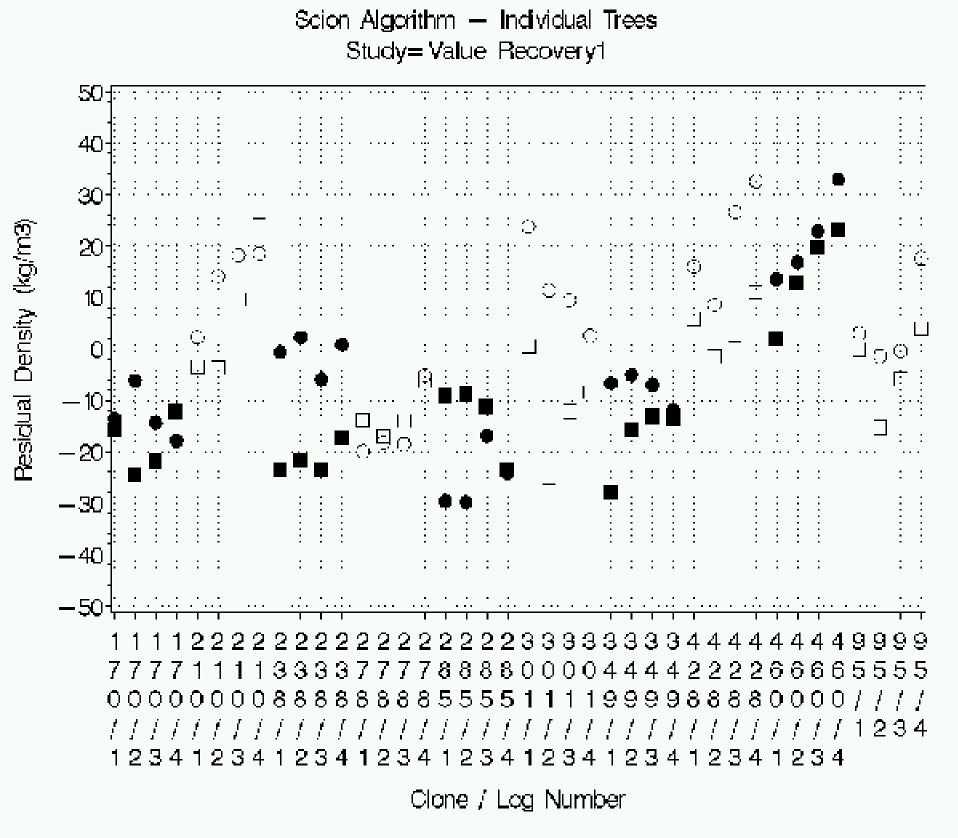

Figure 9a: Value Recovery 1 Clones Study – Scion Residuals

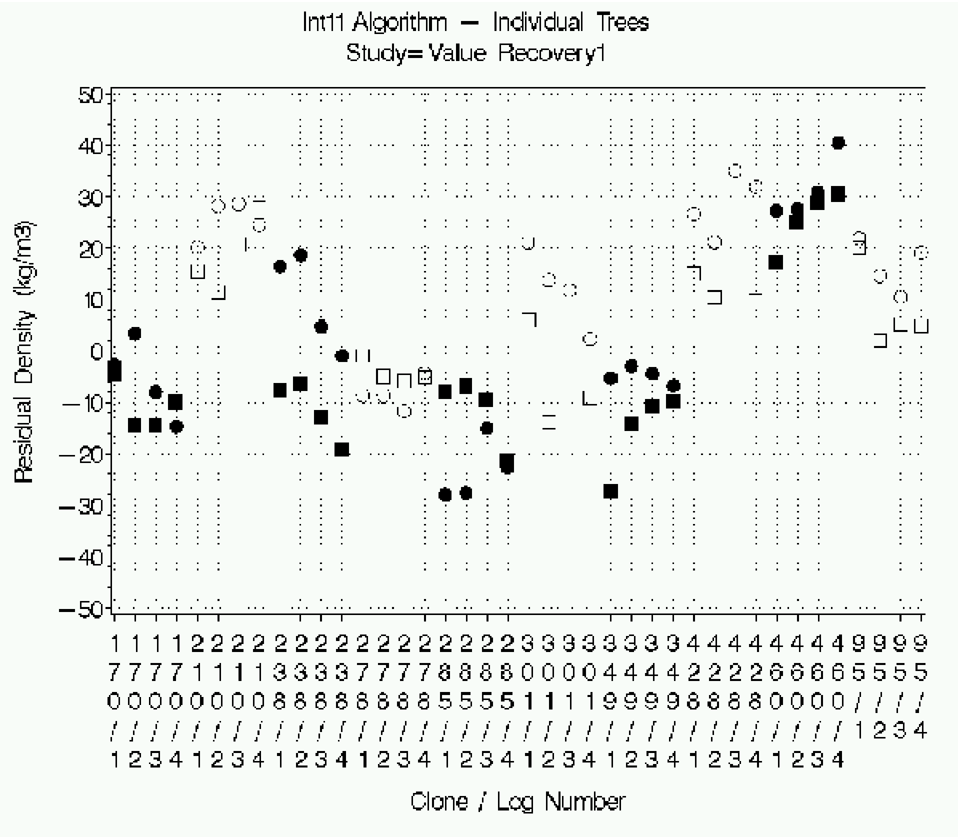

Figure 9b: Value Recovery 1 Clones Study – INT 11 Residuals

Interesting patterns in residuals for clones and trees are evident for the Scion and INT11 models (Figures 9a, b). The patterns for the two ramets of each clone are often similar for a given model. For example, for the Scion algorithm (Figure 9a), the residual density is increasing with log height for clones 210, 428, and 460, decreasing for clone 301, and without a consistent pattern for the other clones. For the INT11 algorithm, the size of the increase in residual is less for clones 210 and 460, and clone 428 is relatively flat. Interestingly, clone 238, which was fairly constant with increased height in the Scion model, decreases with height in the INT11 model. These differences illustrate how density patterns and log height influence the model predictions.

The variance component (Tables 19 and 20) for the clone random effect is similar in magnitude to the 'tree within clone and error' variance component in the lower logs. For logs further up the stem the clone variance component is much larger, accounting for up to 80% of the total variation. This is a direct consequence of each clone having a pattern of within-stem density variation both in the radial direction and with height position that is under a high degree of genetic control. For the Value Recovery clones, the clonal variation in patterns of within-stem density are the dominant cause of model misfit, particularly for logs further up the stem. This is not surprising since the main model predictor is a core of breast height outerwood.

Figure 10 has three examples of clones with large differences in density patterns between clones and very similar density patterns for ramets of the same clone. The genetic variation in within-stem density patterns demonstrated have implications for models such as the Scion model and the WQI INT 11 model that uses a point sample from one location (e.g. a breast height outerwood core) to predict density at other locations in the tree (e.g. the average density for log 4). There are implications for having adequate sample size when estimating model parameters for a given site or silvicultural reqime. Investigations of the influence of site or silviculture on within-tree density patterns would be much more efficient using the same set of clones across sites or for silvicultural treatments.

Table 19: Value Recovery 1 Clones Study – Model Residuals Variance Components

Algorithm	Variance component	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	Clone	101	35	171	289
	Tree within clone and error	113	171	80	63
WQI Int 11	Clone	193	123	222	334
	Tree within clone and error	101	142	71	66

Table 20: Value Recovery 2 Clones Study – Model Residuals Variance Components

Algorithm	Variance component	Residual butt log density	Residual log 2 density	Residual log 3 density	Residual log 4 density
Scion	Clone	42	58	10	174
	Tree within clone and error	69	69	183	116
WQI Int 11	Clone	115	109	62	172
	Tree within clone and error	40	49	158	104

For both the Scion and INT11 algorithms, the variance component for clone is higher for the log 4 residuals than for the butt log residuals (Tables 19 and 20). This probably reflects the fact that clones vary in the pattern of within-tree density variation both radially and vertically – and log 4 is furthest from the location of the breast height outerwood core used as the main predictor variable in both models.

For the Value Recovery 1 and Value Recovery 2 studies, the magnitude of the variance component for clone was larger for the INT11 models than for the Scion models (Tables 16 and 17). This larger clone variance component arises because the INT11 models include tree shape parameters in addition to breast height outerwood density. The tree shape parameters of diameter at breast height and tree height are under a high degree of genetic control. The INT11 models were calibrated using data from a range of sites, and the model coefficients used with the tree shape variables have been calculated to give a best fit with for the calibration dataset (mainly GF14). However, for the Value Recovery clones, where variation is driven by genotype and not site, the INT11 models result in a worse fit, with higher clonal variation in residuals. In contrast, the Scion density model uses breast height outerwood density and tree age at felling, and the tree age at felling is constant for each of these studies, and therefore is not contributing to variation in predicted log densities within each study.

The evidence suggests that generic models are not well suited to dealing with clones. This is hardly surprising, considering that previous studies (Donaldson *et al.,* 1996; Cown *et al.,* 2002) have shown similar clonal behaviour regarding within-stem density levels and patterns of variation. Measured data from this study are shown in Figure 10. The same could apply to families to some extent, particularly if they have been selected for wood density.

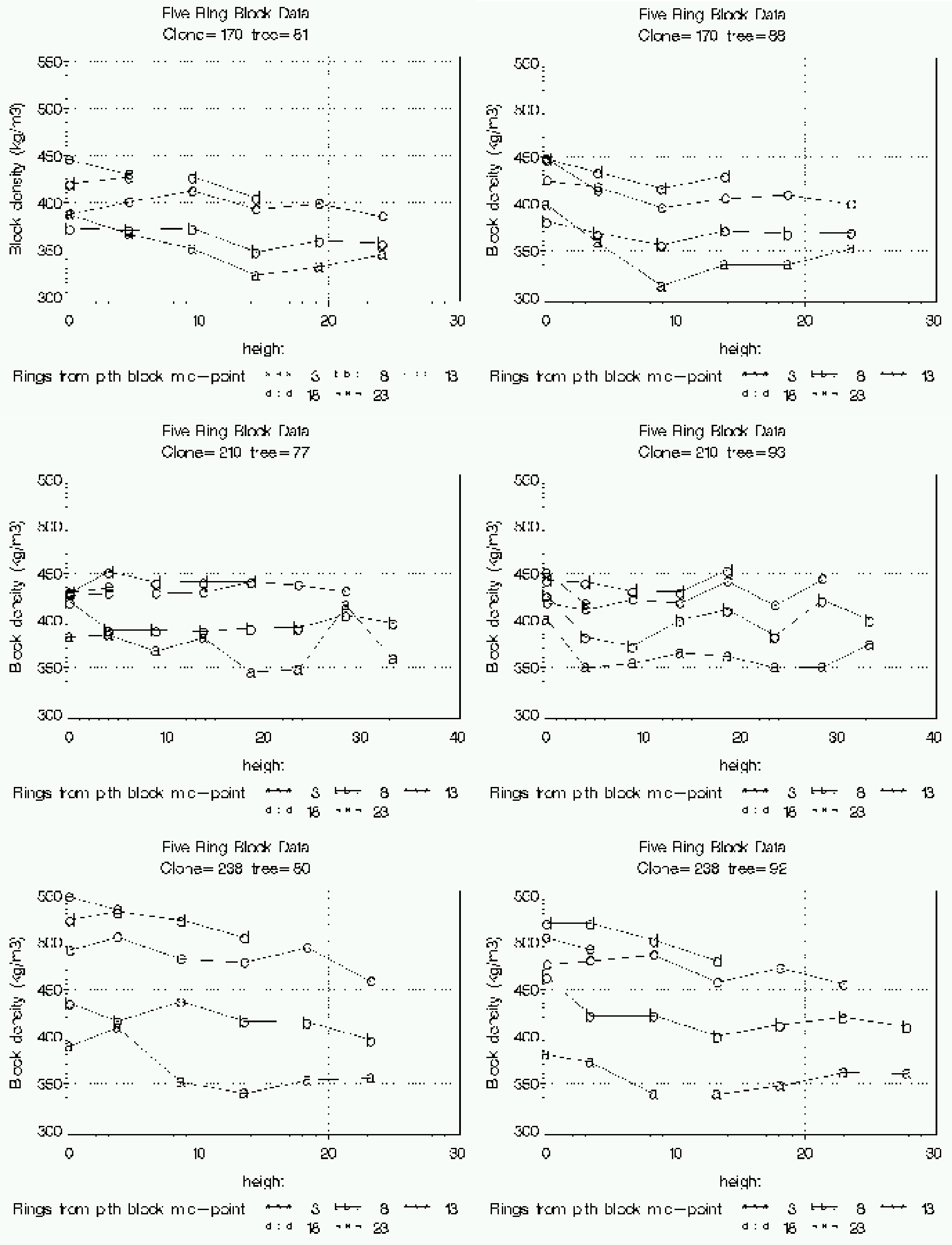

Figure 10: Clonal density trends

a) Cone 170 - both ramets of this clone demonstrate a decrease in density with height position, and a weak radial increase in density from the pith of about 75 kg/m^3.

b) clone 210 – both ramets of this clone demonstrate a flat trend in density with height position, and a weak to moderate radial increase in density from the pith of about 100 kg/m^3.

c) Clone 238 – both ramets of this clone demonstrate a decrease in density with height position, and a strong radial increase in density from the pith of about 150 kg/m^3.

DISCUSSION AND CONCLUSION

We have come a long way in our handling of wood density of radiata pine, and have more sophisticated models than are available for other species around the world. In particular the use of outerwood increment cores greatly improved the efficiency of our assessment methods. There are now several models dealing with aspects of wood density in New Zealand radiata pine. They have been developed with slightly different objectives, but all can be used by forest managers to predict aspects of density variation. There are common data in several of them. The WQI models in particular were intended to offer commercial “algorithms” to industry as an alternative to the Scion Density Algorithm. The intended usage of the two tested models is the same, and differences in approach are minimal; both models appear to be fairly robust. More important is the potential for improvement – presumably very limited in the case of WQI. The use of such models for prediction from very young ages is not recommended, as the use of 50-mm cores in young trees represents a range of biological ages. Nevertheless, there is information available which can be used as a guide in younger crops or even bare sites (Cown *et al.* 1991; Beets *et al.* 2004; Woolons and Manley, 2008). The RPBC have recently reviewed models for predicting forward in time, to quantify the benefits of early assessment (Mark Kimberley, *pers comm*).

Previous models show that the important variables are:

1. Tree genotype
2. Crop age
3. Site Mean Annual Temperature
4. Soil nutrition
5. Silviculture.

The best datasets of wood density happen to be from the North Island, so they were used in the present study. The models themselves were based on national data. The current validation analysis of the Scion and WQI wood density models indicated:

1. Neither model can be expected to deal with the full range of site, silvicultural and genetic possibilities, because the necessary data do not exist, particularly for new breeds. However, both models performed reasonably well across a series of validation studies on test data covering the effects of tree age and spacing. Model residuals for log density predictions were generally well within +/- 40 kg/m^3, and often less than +/- 10 kg/m^3. No model can be expected to perform well on extreme situations not represented by a robust database, but in fact, both Scion and WQI density predictions appear to be fairly robust.

2. The validation using clonal data confirmed that large differences in residuals can occur due to the different within-stem density patterns between clones. To be useful for clones, models must be customised on actual clonal data.

3. The key to more precise prediction of log densities from density measured on the outerwood at breast height is accounting for the pattern of density distributions within a tree, and clearly there are genetic differences in both clones and families in wood density and stiffness (Cown and Ball, 2001; Lasserre *et al.,* 2004; Waghorn *et al.* 2007; Cown *et al.* 2004). Clones will be a challenge in this regard, as the patterns do not become apparent until the trees are mature.

The prediction of density into the future is an issue which so far has been dealt with by constructing a database with a wide range of ages. It is not simple to compare the wood formed at different ages within stems due to heartwood development. There is also an issue with using samples from young trees (less than 15 years) in that 50-mm cores often represent very different biological wood ages, and traditionally in young stands samples were selected to cover a specific number of growth rings (e.g. 5 rings). The samples from young trees also represent wood which will become heartwood in mature stems, introducing another factor.

The accuracy required for stem density predictions may not be very high, particularly as:

1. Site averages may be most relevant and used for comparisons or forward predictions.
2. If density is used as an indication of stiffness, other factors, mainly branch size, are also very important (machine grades require validation of both stiffness and strength, and often have a visual over-ride for knot size).

Wood density assessments and predictions are likely to remain very important in forest growing, because at the moment they are relatively easy to collect, and robust. Other methods such as acoustics may eventually supersede density, but only when they are fully validated and other factors are incorporated (actual green density, branch size).

Future Model Development

Many models have been published for relating wood characteristics, such as wood density, to growth traits, and there is an international trend to linking growth and wood quality models. Wood density is likely to remain a highly topical issue for a number of reasons, particularly carbon sequestration (for foresters) and product performance and value (wood processors).

At a tree population level, ring density is known to be significantly correlated with cambial age and ring width. However, at the individual tree level, the predictive value of models based on this relationship is usually poor, as there is an important, so-called "tree effect" in the residuals of such models. This effect probably arises mainly from within-stand genetic variability. The addition of a genetic effect would significantly increase the predictive value of models and decrease the residuals. At the clone level, for instance, the inclusion of a genetic effect increased the explained variance (adjusted R^2 value) from 20% to 54% in a Douglas-fir study (Rosenberg *et al.,* 2001).

Any approach adopted by FFR should be capable of linking to available growth models to better deal with site and silvicultural effects, and to cater for continual improvement through additional new knowledge and data. By far the most comprehensive data on wood density and modelling expertise is at the disposal of Scion. This does not preclude collaborative arrangements with other modellers for future development.

Models based on breast height outerwood density measurements need to be able to predict both average density and density variation, with adjustments based on other easily measured or known variables (e.g. tree age, site information, stocking, seed source). There are several approaches currently used (initial density, climatic factors, soil factors, silvicultural measures), and in the future other drivers may be used. In the Effect of Crop Age Study, significant correlations were discovered between branch characteristics and the model residuals, which suggests a useful additional factor for further investigation.

The enhancement of models will be ongoing and should focus on:

- Early prediction of log and stem densities (including estimates for bare land)
- Improving predictions from site and silvicultural data
- Gradually including a wider range of breeds
- Predicting density values for individual stems and logs.

To achieve the best results for FFR shareholders it will be desirable to combine all existing wood density data into a single National Database, along with new data resulting from future studies. This would allow FFR to focus on gaps in the data and update functions regularly. Particular attention should be given to a “seamless” transition in predictions from young crops (less than 15 years) and mid-rotation and older crops. For carbon sequestration purpose it will also be desirable to extend the data base to, say, 50 years.

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REFERENCES

Beauregard, R.L., Gazo, R., Ball, R.D. 2002: Grade recovery, value and return-to-log for the production of NZ visual grades (cuttings and framing) and Australian machine stress grades. Wood and Fiber Science 34(3): 485-502.

Beauregard, R.L., Gazo, R., Kimbrley, M.O., Turner, J., Mitchell, S., Shelbourne, A. 1999: Clonal variation in the quality of radiata pine random width boards. Wood and Fiber Science 31(3): 222-234.

Beets, P N; Cown, D J; Graham, J D; Kimberley, M O; McConchie, D L 2004: Variation in outerwood density in relation to site factors – 1978 Genetic Gains Trial. WQI Report RES 15: 22pp.

Beets, P N; Kimberley, M O; McKinley, R B; 2007. Predicting wood density of Pinus radiata annual growth increments. New Zealand Journal of Forestry Science 37(2): 241-266. New Zealand Journal of Forestry Science 37(2): 241-266

Beets, P.N. 1997: Wood density and nitrogen supply. Pp. 23–24 *in* Ridoutt, B.G. (Ed.) "Managing Variability in Resource Quality", Proceedings of the 2nd New Zealand Wood Quality Workshop, 12 September 1997. *New Zealand Forest Research Institute Limited, FRI Bulletin No. 202*.

Beets, P.N.; Gilchrist, K.F.; Jeffreys, M.P. 2001: Wood density of radiata pine: effect of nitrogen supply*. Forest Ecology and Management 145*: 173–180.

Cown, D.J. 1974a: Wood density of radiata pine: its variations and manipulation. New Zealand Journal of Forestry 19(1): 84-92.

Cown, D.J. 1974b: Comparison of the effect of two thinning regimes on some wood properties of radiata pine. New Zealand Journal of Forestry Science 4(3): 540-551.

Cown, D.J. and McConchie, D.L. 1981: Effects of thinning and fertiliser application on wood properties of *Pinus radiata*. New Zealand Journal of Forestry Science 11(2): 79-91.

Cown, D.J. and McConchie, D.L. 1982: Wood density prediction for radiata pine logs. New Zealand Forest Service, FRI Bulletin No. 9.

Cown, D.J., McConchie, D.L. and Young, G.D. 1991: Radiata pine wood properties survey. FRI Bulletin No. 50 (revised).

Cown, D.J., McKinley, R.B., Ball, R.D. 2002: Wood density variation in 10 mature *Pinus radiata* clones. NZ Journal of Forestry Science 32(1); 48-69.

Cown, D.J., van Wyk, J.L. 2004: Profitable wood processing – what does it take? Good wood! New Zealand Journal of Forestry 49(1): 10-15.

Cown, D.J.; Ball, R. 2001: Wood densitometry of ten *Pinus radiata* families at seven contrasting sites: Influence of tree age, site and genotype. New Zealand Journal of Forestry Science 31(1): 88-100.

Cown, D.J.; Ball, R.D.; Riddell, M. 2004: Wood density and microfibril angle in plantation radiata pine: Distribution and influence on product performance. New Zealand Journal of Forestry Science 34(3): 293-315.

Donaldson, L., Evans, R., Cown, D.J., Lausberg, M. 1996: Clonal variation of wood density variables in *Pinus radiata*. NZ Journal of Forestry Science 25(2): 175-188.

Harding, V.O., Orange, R.P. 1998: The effects of juvenile wood and lay-up practices on various properties of radiata pine laminated veneer lumber. Forest products Journal 48(7/8): 63-70.

Harris, J.M. 1965: A survey of the wood density, tracheid length, and latewood characteristics of radiata pine grown in New Zealand. New Zealand Forest Service, FRI Technical Paper N0. 47: 31pp.

Lasserre, J.-P., Mason, E.G., Watt, M.S. 2004: The effects of genotype and spacing on *Pinus radiata* corewood stiffness in an 11-year-old experiment. Forest Ecology and Management 205: 375-383.

Lausberg, M.J.F., Donaldson, L.A. 1994: Documentation of wood quality results from a clonal pulping study – compartment 327. NZ Forest Research Institute Project Record No. 3978 (unpublished): 39pp.

Mason, E., Dzierzon, H. 2007: Analysis of National Benchmarking Study. WQI Report RES 35: 54pp.

McKinley, R.B. 2000: Wood properties of 35-year-old *Pinus radiata* from the Tarawera Regimes Trial. Scion Report (unpublished): 39pp.

McKinley, R.B., McConchie, D.L., Gilchrist. K.F. 1994: Utilisation of a 21-year-old new crop radiata pine stand. Part 1: Wood properties. NZ Forest Research Institute Project Record No. 3884 (unpublished): 42pp.

McKinley, R.B., Ridoutt, B., McConchie, D.L., Lausberg, M.J.F. 1996: Density variation in tn 27-year-old radiata pine clones from Kaingaroa Forest. Value Recovery Rreport (unpublished): 16pp.

McKinley, R.B., Young, G.D., McConchie, D.L. 1993: Effect of spacing on wood properties of 19-year-old radiata pine grown under an agroforestry regime. NZ Forest Research Institute Project Record No. 3424 (unpublished): 49pp.

McKinley, R.B., Young, G.D., McConchie, D.L., Gilchrist. K.F. 1994: Utilisation of a 30-year-old new crop radiata pine stand. Part 1: Wood properties. NZ Forest Research Institute Project Record No. 3447 (unpublished): 39pp.

Pont, D., Grace, J., Gordon, A., Shula, B. 2002: A guide to using TREEBLOSSIM Version 1.2. SGMC Report No. 113: 32pp.

Pont, D. 2003: A model of secondary growth for radiata pine. M.F.Sc. Thesis, University of Canterbury, Christchurch: 183pp.

Rawley, B. 2006: Basic density models. WQI Report INT 7: 30pp.

Rawley, B. 2007: Basic density model updates. WQI Report INT 11: 28pp.

Raymond, C.A., Joe, B. 2007: Patterns of basic density variation for *Pinus radiata* grown in south-east slopes region of New South Wales, Australia. New Zealand Journal of Forestry Science 37(1): 81-95.

Roper, J., Ball, R., Davy, B., Downes, G., Fife, D., Gunt, D., Gritton, D., Ijic, J., McKinley, R., Morrow, A., Northway, R., Penellum, B., Rombouts, J. Pongracic, S. 2004: Resource evaluation for future profit. Part A- Wood property survey of the Green Triangle region. FWPRDC Report PN03.3906: 75pp.

Rosenberg, P., Franc, A., Bastien, C., Cahalan, C. 2001: Improving models of wood density by including genetic effects: A case study in Douglas-fir. Ann. For. Sci. 58 (2001) 385-394.

Tian, X., and Cown, D.J 1995: Modelling of wood properties. Presentation to NZFRI Wood Quality Workshop, Rotorua, November 1995. EDS Klitscher, Cown and Donaldson. FRI Bulletin No. 201.

Tian, X., Cown, D.J. and McConchie, D.L. 1996: Modelling of Radiata Pine Wood properties. Part 2: Wood density. NZ Jour. of Forestry Science 25(2): 214-230.

Tian, X., Cown, D.J. and Ridoutt, B. 1997: Algorithm for predicting sawlog and pulpwood density using outerwood density at breast height. Value Recovery Report (confidential).

Waghorn, M.J., Watt, M.S., Mason, E.G. 2007: Influence of tree morphology, genetics, and initial stand density on outerwood modulus of elasticity in 17-year-old *Pinus radiata*. Forest Ecology and Management244: 86-92.

Woolons, R. and Manley, B. 2008: Prediction of stand diameter breast height outerwood density through topographic and growth predictor variables. WQI Report INT 15: 9pp.

Young, G.D., McConchie, D.L., McKinley, R.B. 1991: Utilisation of a 25-year-old new crop radiata pine stand. Part 1: Wood properties. NZ Forest Research Institute Project Record No. 2835 (unpublished): 54pp.

Young, G.D., McKinley, R.B., Cown, D.J., McConchie, D.L. 1992: Utilisation of a 26-year-old new crop radiata pine stand. Part 1: Wood properties. NZ Forest Research Institute Project Record No. 3203 (unpublished): 45p.