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A nationwide *Eucalyptus regnans* growth model

C.M. MacLean and M.E. Lawrence

NZFRI

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Abstract

A model for predicting growth and yield of managed *Eucalyptus regnans* F. Muell. has been constructed. Stand level increment models were derived for mean top height, basal area, stocking and volume. A model to simulate thinning was also constructed. Data was sourced from young (less than age 20) plantation type stands from throughout New Zealand, with the majority from the Central North Island.

The basal area and mortality models are a multi-variate generalisation of the Bertalanffy-Richards where changes in the stand (eg. growth, mortality) are modelled by a system of stochastic differential equations, with the parameters estimated using maximum likelihood techniques. Height growth is modelled using the Bertalanffy-Richards linear differential equation.

Keywords: growth; yield; *Eucalyptus regnans*.

Introduction

Eucalyptus regnans F. Muell., mountain ash, occurs naturally in the States of Victoria and Tasmania of south eastern Australia, on sites ranging from sea level in Tasmania to approximately 1100 metres in parts of Victoria. In these areas, rainfall ranges from 750 to 1700 millimetres per annum, with a winter maximum. The mean maximum monthly temperature is 23°C and the minimum monthly temperature is between 0 and 2°C. *E. regnans* is frost tolerant, and up to 80 frosts per annum may be encountered at higher elevations. (FAO, 1979).
E. regnans is an important commercial species in Australia where it is used in construction, veneer and plywood, and is one of the most important species used in the pulp and paper industry (Hillis & Brown, 1984)

Eucalypts were some of the first exotic hardwoods to be planted in New Zealand (Weston, 1957). The ash group eucalypts such as *E. regnans, E. fastigata, and E. delegatensis* were some of the more widely planted, due to their relative resistance to insect attack by the eucalyptus tortoise beetle (*Paropsis charybdis*), the gum tree scale (*Eriococcus coriaceus*) and the gum tree weevil (*Gonipterus scutellatus*). These tree species were also found to have a fair level of frost tolerance, relatively good growth and form, and provided timber and arisings that were suitable in a range of uses.

Interest in *E. regnans* at a commercial level began in the 1960's with the establishment of significant areas by NZFP Ltd. (now Carter Holt Harvey Forests Ltd.) as a hardwood pulp resource. By 1980, this resource comprised approximately 40% of the eucalypt resource in New Zealand (Fry, 1983).

In the late 1970's the New Zealand Forest Service introduced a policy of small scale plantings of "minor" species, with a requirement for total annual plantings of special purpose species to be 2100 ha, including a minimum of 1290 hectares per annum in eucalypts (NZFS, 1981). The development of the Special Purpose Species Policy provided a formal guideline for research into species such as *E. regnans* During this period eucalypt plantings (mostly private) in the Central North Island region focused primarily on *E. regnans* (McKenzie, *pers comm*[1]). However by the late 1980's *E. regnans* was no longer favoured as a major eucalypt species due to concerns over health, and bio-control of insect agents that had previously hampered the success of other eucalypts.

Background to growth model development

At the second meeting of the Management of Eucalypts Cooperative in December 1986, the development of a growth model for *E. regnans* was mooted. An *E. regnans* growth model had already been developed by NZ Forest Products Limited (Hayward 1988) using data from the Kinleith region, and had been released to members of the Management of Eucalypts Cooperative as Report No. 4 in 1988. However the need for a growth model based on more extensive data and which incorporated the facility to model thinnings was identified. The development of growth functions based on the national *E. regnans* database commenced in 1993.

DATA

Data are primarily from Permanent Sample Plots (Pilaar and Dunlop 1989) located in the central North Island of New Zealand (70%), but also include plots distributed from Southland to North Auckland. The database originally contained 1797 measurements from 427 plots nationwide, however a number of measurements were found to be unsuitable or unreliable due to missing or illogical data and were subsequently deleted.

The final database contained 900 measurements from 138 plots. Table 1 contains a summary of data. Figures 1-4 illustrate the range of data used in the model.

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[1] Heather McKenzie is a scientist researching New Zealand grown eucalypts and is based at the New Zealand Forest Research Institute.

Table 1- Data summary

	Age years	SI	MTH m	Stems/ha	BA m^2/ha	MAI	Volume m^3/ha
Mean	9.7	35.9	20.2	612	14.6	10.93	119.5
Min	3.2	25.8	5.8	50	1.1	0.77	3.6
Max	32.2	48.2	55.7	2900	76.4	51.04	1226.2

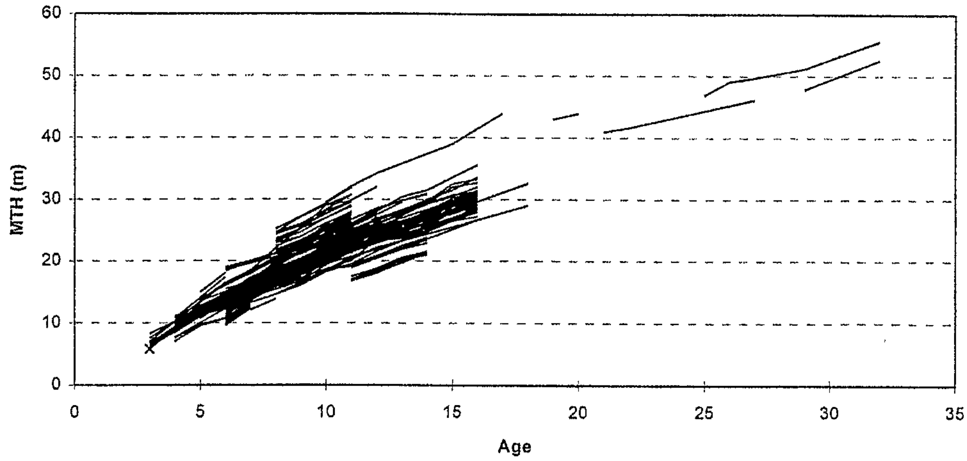

Figure 1- Mean top height v age

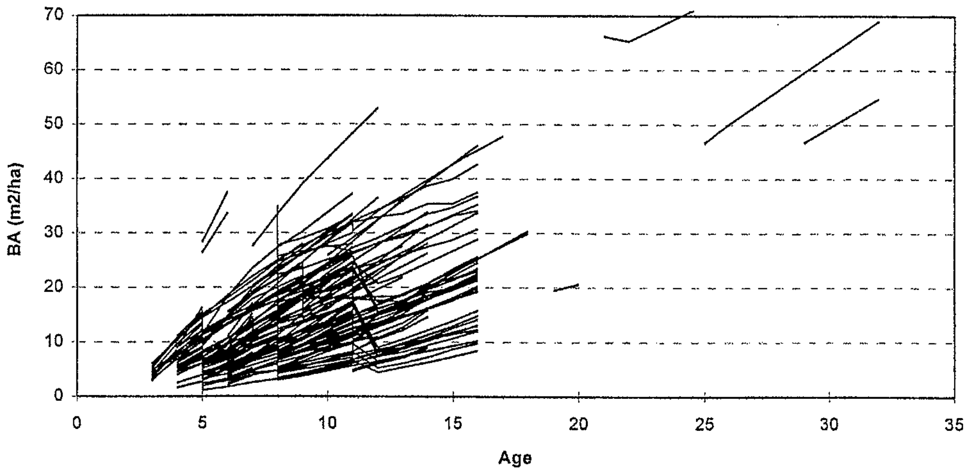

Figure 2- Basal area v age

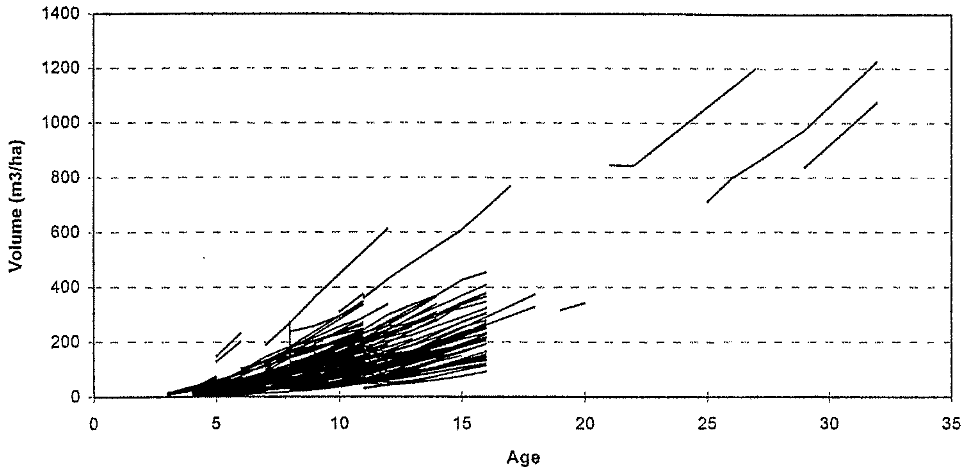

Figure 3- Volume v age

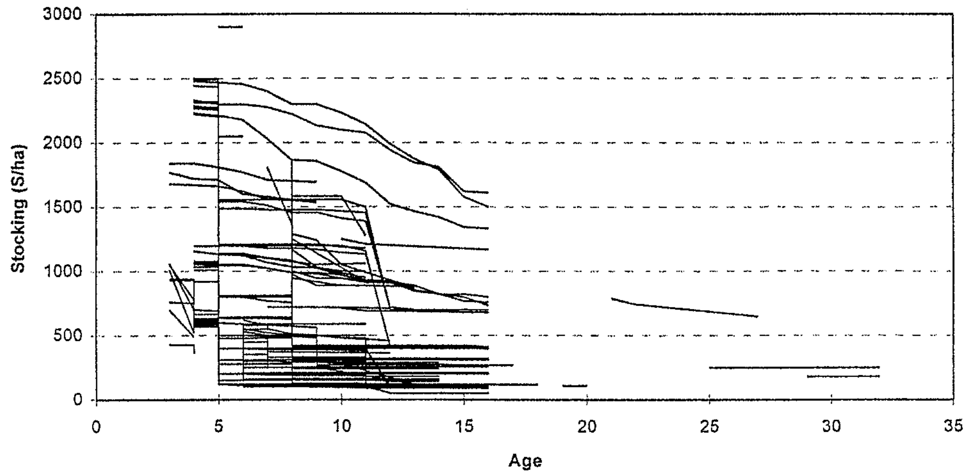

Figure 4- Stocking v age

The bulk of the data lies between the ages of 4 to 16 years. As shown in Figure 3, total stand volumes at age 16 are highly variable, ranging from 100m³/ha to in excess of 400m³/ha.

MODEL DEVELOPMENT

Height growth

Mean Top Height (MTH) is defined as the height of the mean of the100 largest diameter trees per hectare. It is computed by calculating the quadratic mean diameter of the 100 largest diameter trees and fitting a Petterson height/diameter regression to a sub-sample of trees in a plot Mean top height is derived from the regression curve for a tree of this diameter (McEwen, 1978).

Measures of top height are seldom affected by stand density over a wide range of silvicultural treatments, although some reduction in growth has been found in more extreme cases. In *E. regnans* this assumption has been found to be correct (McKenzie & Kimberley, 1993). The methodology assumes that height increment is a function of the current height, as adopted in the commonly used Bertalanffy-Richards (1949, 1957, 1959) equation. This function can be written as a linear differential equation substituting a transformation H^c for H such that:

$$\frac{dH^c}{dt} = b\,(a^c - H^c) \qquad \text{....(1)}$$

where H = mean top height (m)

t = age (years)

b and c = coefficients

For a given height-age pair, integration of (1) enables the calculation of height at any other age, t, such that:

$$H = a\left(1-\left(1-\frac{H_0^c}{a^c}\right)e^{-b(t-t_0)}\right)^{1/c} \qquad \text{....(2)}$$

where H = mean top height (m)

t = age (years)

H_0 = mean top height (m) at t_0 years

t_0 = age (years) at H = 0 m

Parameter a is the asymptotic height as $t \rightarrow \infty$, b is a 'time scale' factor which may be used to modify the rate of growth as in (3), and parameter c determines the shape of the curve.

By utilising a or b or a linear combination of the two, site index curves can be developed from (2) for any particular set of data. A number of parameter combinations were tried and maximum likelihood estimates used to compare models (Garcia, 1983, 1984). However best results have been obtained using b such that:

$$b = \frac{-\ln\left(1-\left(\frac{S}{a}\right)^c\right)}{20 - t_0} \qquad \text{....(3)}$$

where S = site index (m) at age 20 years (and assuming H_0^c = 0).

After substituting (3) in equation (2) and rearranging, it is possible to estimate site index from a given mean top height and age such that:

$$S = (a \times (1-(1-\left(\frac{H}{a}\right)^{c})^{\left((20-t0)/(t-t0)\right)})^{\left(1/c\right)} \qquad \text{....(4)}$$

In all of the above equations

t = age (years)
H = mean top height (m)
S = site index (m)

a = 137.38
c = 1.0809
t_0 = 0.0

Figure 5 shows the results of the height model for site indices of 20, 35, and 50m superimposed on the original height data. The model residuals are given in Figure 6.

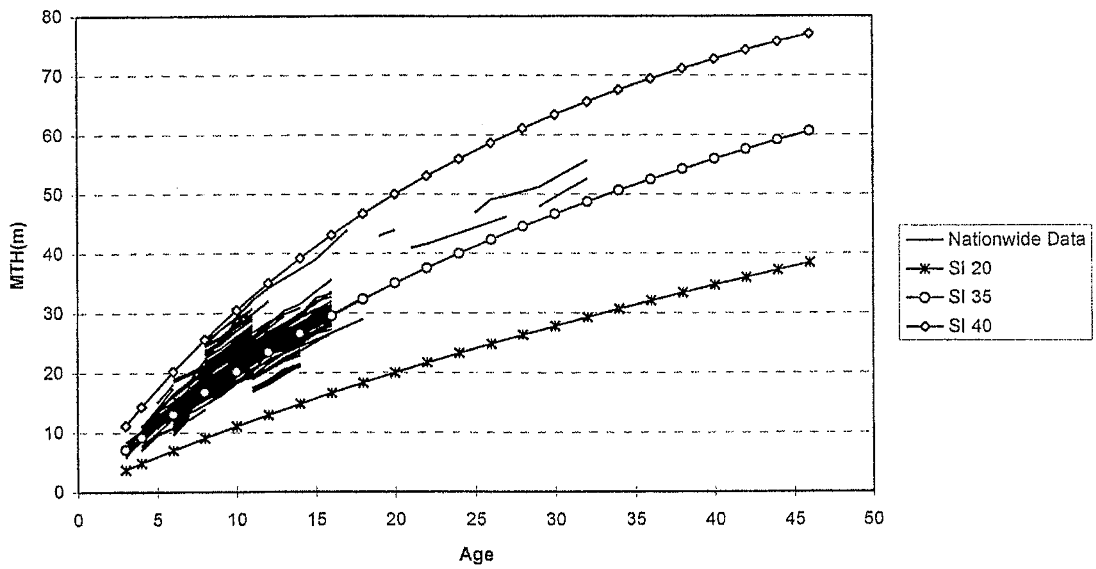

Figure 5- Mean top height v age

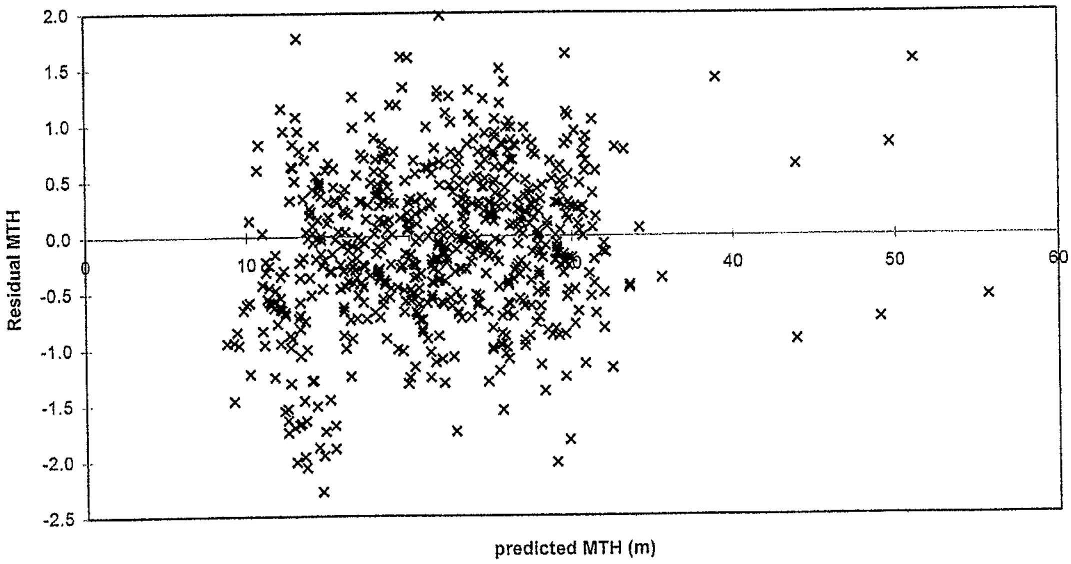

Figure 6- Mean top height residuals[2]

Stand growth

The equations to model stand growth are a multi-variate generalisation of the Bertalanffy-Richards model, Garcia (1979, 1984). The current state of the stand is described by a combination of stand basal area, stocking and mean top height, in conjunction with a number of parameters to be estimated. Changes in the stand (eg. growth, mortality) are modelled by a system of stochastic differential equations, with the parameters estimated using maximum likelihood techniques.

The general form of the model is:

$$\frac{dB^{c11}N^{c12}H^{c13}}{dt} = a_{11}B^{c11}N^{c12}H^{c13} + a_{12}B^{c21}N^{c22}H^{c23} + a_{13}H^{c33} + b1$$

$$\frac{dN^{c22}}{dt} = a_{21}B^{c11}N^{c12}H^{c13} + a_{22}B^{c21}N^{c22}H^{c23} + a_{23}H^{c33} + b2$$

$$\frac{dH^{c33}}{dt} = -H^{c33} + b3$$

....(5)

The first two equations model basal area growth and changes in stocking respectively. The third equation models height growth and is estimated separately, as previously described, assuming *a priori* that height growth is independent of stand density.

Parameter estimates were obtained by using a general purpose optimisation algorithm to obtain the maximum log-likelihood estimate for a given model formulation (Biggs, 1971, 1973; N.O.C., 1976). A number of variations were evaluated, commencing with simple combinations involving few parameters, to more complex models with few constraints on model behaviour. At each stage the models were evaluated by calculating the residuals and examining their behaviour.

The selected model is conditioned to exclude increase in stocking due to ingrowth.
The parameter estimates for the adopted model are:

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[2] All charts show residuals as actual - predicted values

$$C = \begin{pmatrix} -0.10465 & 0.014741 & 1.0843 \\ 0 & -0.34935 & 0 \\ 0 & 0 & 1.08089 \end{pmatrix} \qquad b = \begin{pmatrix} 151.01 \\ 0 \\ 204.58 \end{pmatrix}$$

$$A = \begin{pmatrix} 2.3945 & -73.2072 & -2.69566 \\ 1.67116E-4 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

λ_1= 2.38937
λ_2= 5.12018E-3
λ_3= -1

$$a = \begin{pmatrix} 0 \\ -5.47034 \\ 204.576 \end{pmatrix} \qquad P = \begin{pmatrix} 1 & -30.6370 & -0.795289 \\ -6.99440E-5 & 1 & 1.87578E-4 \\ 0 & 0 & 1 \end{pmatrix}$$

where $a=-A^{-1}b$ ....(6)

Lambdas 1, 2, and 3 are the eigenvalues of A. The rows of P are the left eigenvectors such that:

$$A = P^{-1}\Lambda P$$

and lambdas 1, 2, and 3 are the elements on the diagonal of Λ. See Garcia (1984) for a more detailed explanation of these parameters.

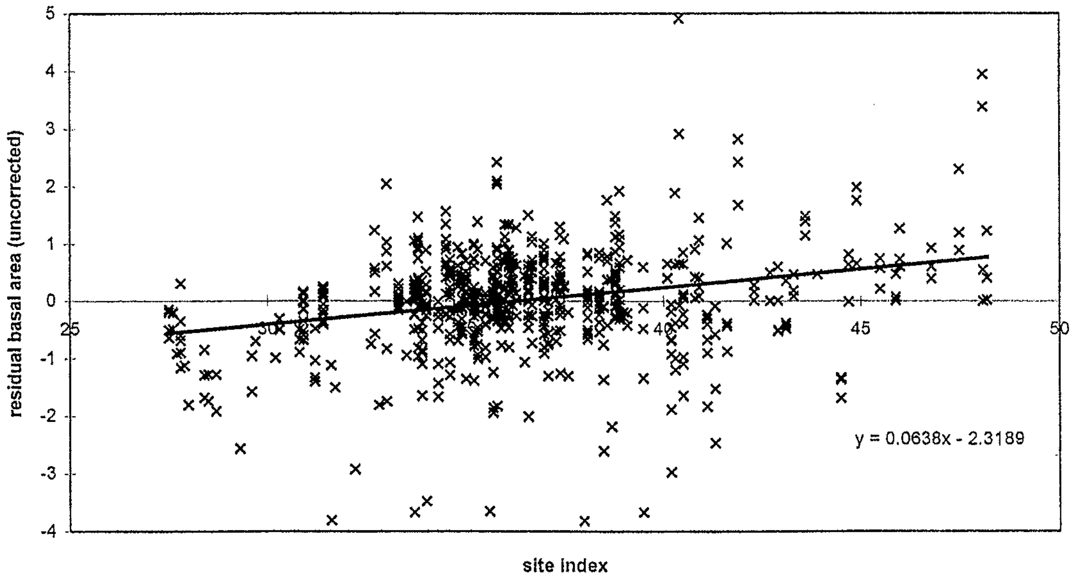

Figure 7- Uncorrected basal area residuals v site index

Analysis of the basal area residuals from (4) (Figure 7) indicates a relationship between basal area increment and site index that is not fully explained by the model. This bias is shown by the trendline displayed in Figure 7.

The source of the bias could not be readily identified through further examination of the original data. Although it has not been possible to identify the cause of the bias, it is possible to modify the predictions and thus remove any error. The modifier developed was:

$$CBA = MBA - (a + b \times S) \qquad \ldots(7)$$

where **CBA** = corrected basal area (m^2/ha)
MBA = model basal area (m^2/ha)
S = site index (m)

a = -2.039
b = 0.057

The results can be seen in Figure 8. The trend apparent in Figure 7 has been nullified with the inclusion of the correction. Figure 9 shows basal area residuals against predicted basal area.

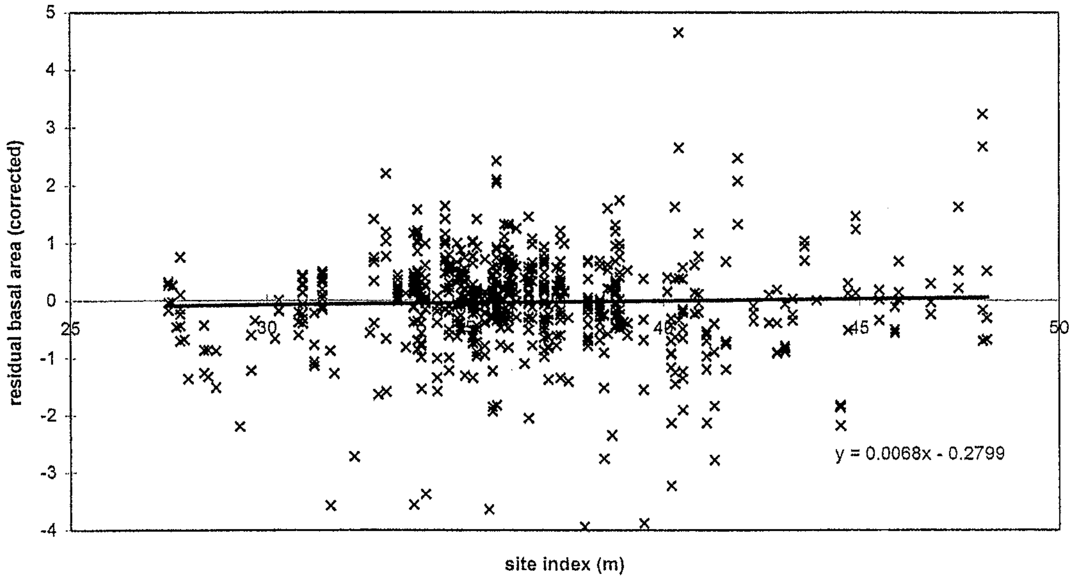

Figure 8- Corrected basal area residuals v site index

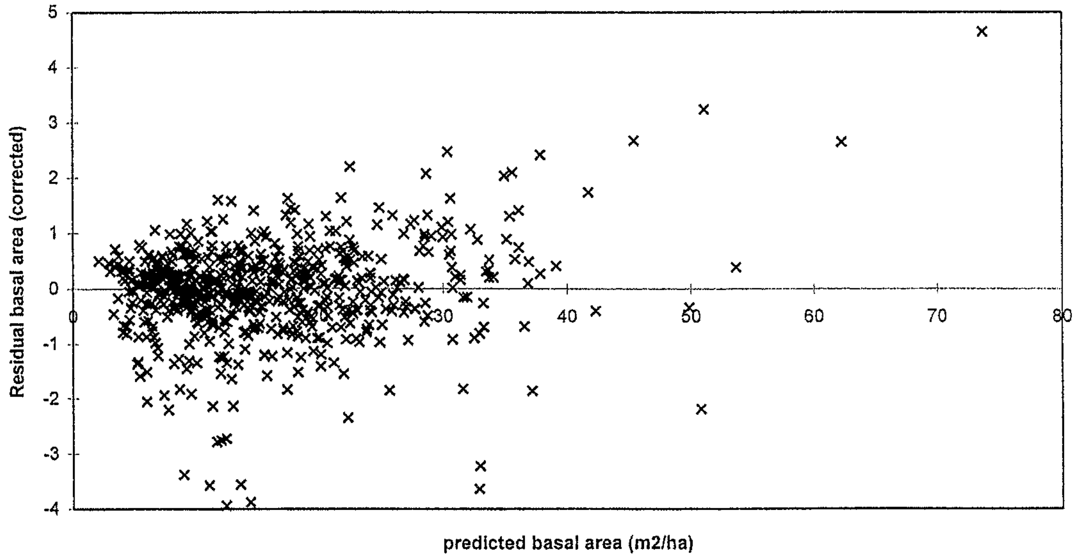

Figure 9- Corrected basal area residuals v predicted basal area

Initial basal area function

The series of differential equations used to predict basal area growth and mortality, behave satisfactorily within the range of the data. However outside this range, at ages less than 4 years, growth predictions are likely to be less reliable. To overcome this, a separate function has been developed to model growth from age zero and provide a starting point for subsequent growth.

Data used in the development of this function were restricted to first measurements of plots aged less than ten years, where no thinning or severe mortality had previously occurred. The 27 plots that fulfil these criteria are summarised in Table 2.

Table 2- Summary of data used for initial basal area function

	Age years	MTH m	Plot SI	BA m^2/ha	Stems/ha
Mean	3.9	9.0	35.3	6.9	1619
Min	3.0	6.1	30.5	3.8	1010
Max	5.0	10.7	38.9	11.0	2489

$$IBA = a \times N^{0.5} \times H^{b} \qquad \textbf{....(8)}$$

corrected $r^2 = 0.852$

Where: **IBA** = initial basal area (m^2/ha)
N= stocking (stems/ha)
H = mean top height (m)

a= 0.009363
b= 1.3491

Residuals for the initial basal area model are shown in Figures 10-12

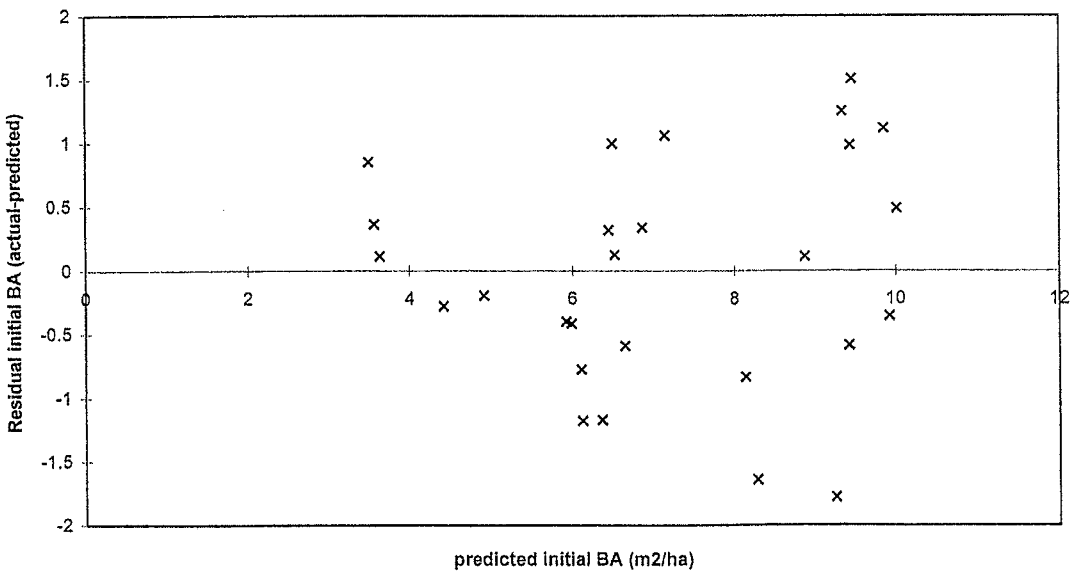

Figure 10- Initial basal area residuals

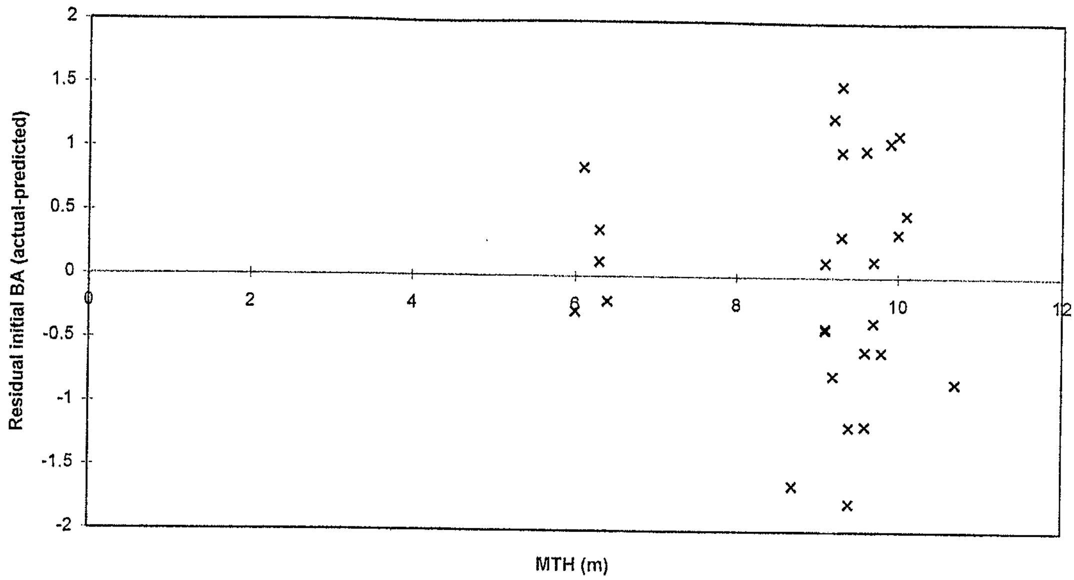

Figure 11- Initial basal area residuals v mean top height

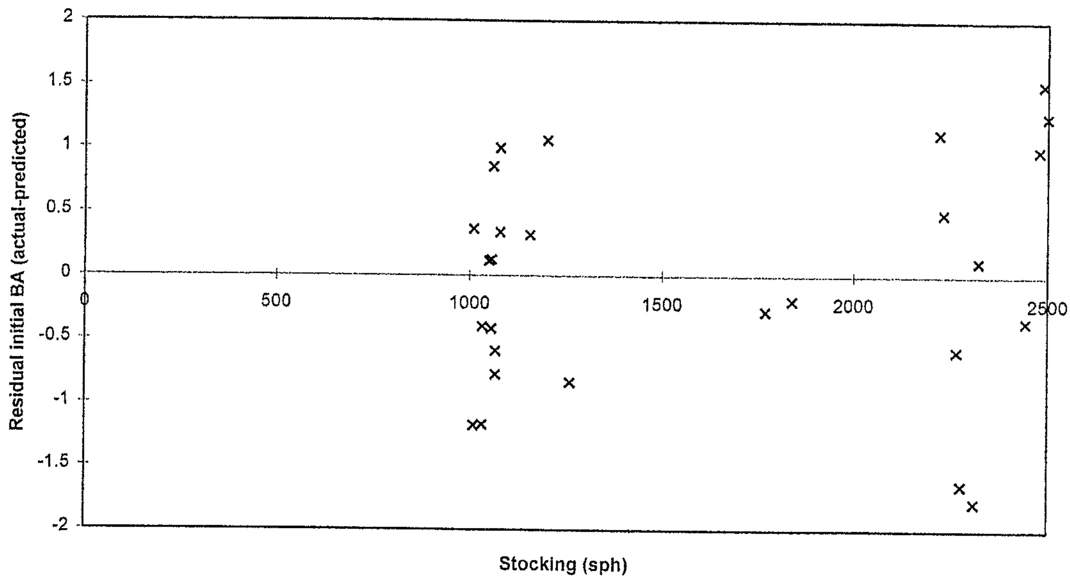

Figure 12- Initial basal area residuals v stocking

Thinning function

In order to model regimes incorporating one or more thinnings, it is necessary to develop a function to predict the state of a stand following a thinning operation. Data from 52 plots containing 154 measurements representing 66 thinnings were used to develop an equation to predict stand basal area after thinning, given the stocking before thinning and the number of stems removed. These data are summarised in Table 3.

Table 3- Thinning data summary

	Thin Age (years)	Initial Stocking (stems/ha)	Thinned Stocking (stems/ha)	% BA removed (m^2/ha)
Mean	6.4	939	425	38.9
Min	4.0	200	100	1.4
Max	11.0	2500	1556	77.2

The general form of the function is:

$$B = (B_0^{-q} - p \times \frac{q}{r} \times (N^r - N_0^r))^{(\frac{-1}{q})} \qquad ....(9)$$

Where:

B = basal area after thinning
$\mathbf{B_0}$ = basal area before thinning
N = stocking after thinning
$\mathbf{N_0}$ = stocking before thinning

q = 0.134
p= 2.2124
r= -0.233

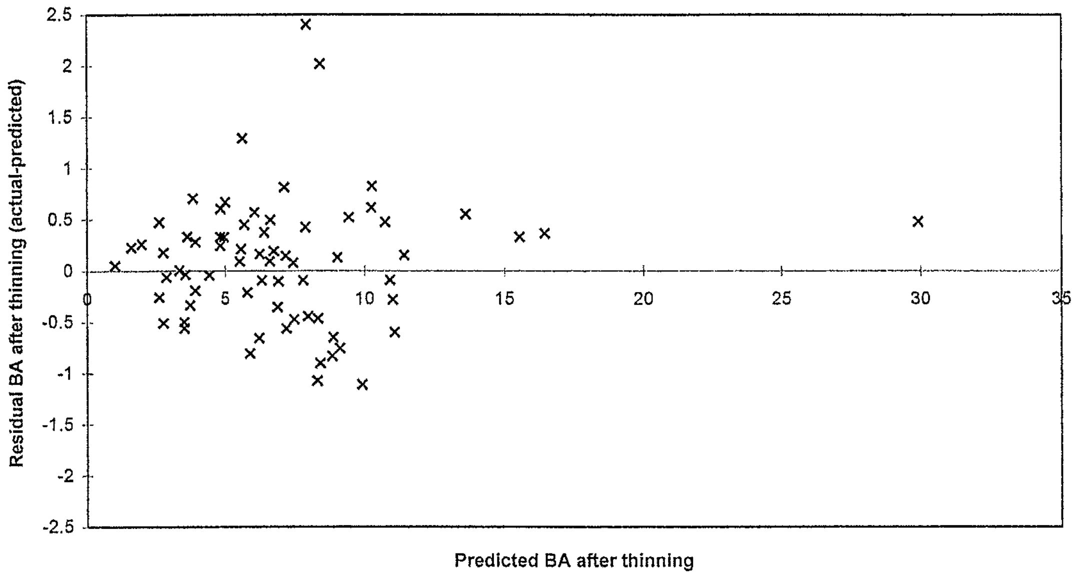

Figure 13- Residuals for thinning model

Residuals from this model (Figure 13) are unbiased and normally distributed. The two outliers (at y=2 and y=2.4) represent anomalous thinning events where large numbers of very small diameter trees were removed with only a minimal reduction in stand basal area.

Stand volume function

Total stand volume is obtained by combining estimates of stand parameters in a stand volume equation derived from Permanent Sample Plot data. Sample plot volumes were obtained by using the Hayward tree volume equation derived from data from the Central North Island (Hayward, 1987) in conjunction with tree diameter and height measurements. The individual tree values were then aggregated to the stand level to give estimates of total standing volume, basal area, mean top height and stocking.

A total of 489 measurements from 122 plots were used to derive a function for *E. regnans*. These are summarised in Table 4.

Table 4- Stand volume data

	Age (years)	**Basal area** (m^2/ha)	**Mean top height** (m)	**Stocking** (stems/ha)	**Volume** (m^3/ha)
Mean	9.6	11.3	19.8	406	90.5
Min	3.3	1.1	6.4	50	3.6
Max	29.3	46.8	47.9	2900	835.6

A number of transformations of the stand variables were evaluated and the final model estimated using stepwise regression analysis. The resulting equation is:

$$V/B = a + b \times H + c \times N^d \qquad \textbf{....(10)}$$

adjusted $r^2 = 0.988$

Where B = basal area (m^2/ha)
N = stocking (stems/ha)

a = -1.3396
b = 0.35739
c = 6.3951
d = -0.26855

Residuals for the basal area model are shown in Figures 14 and 15.

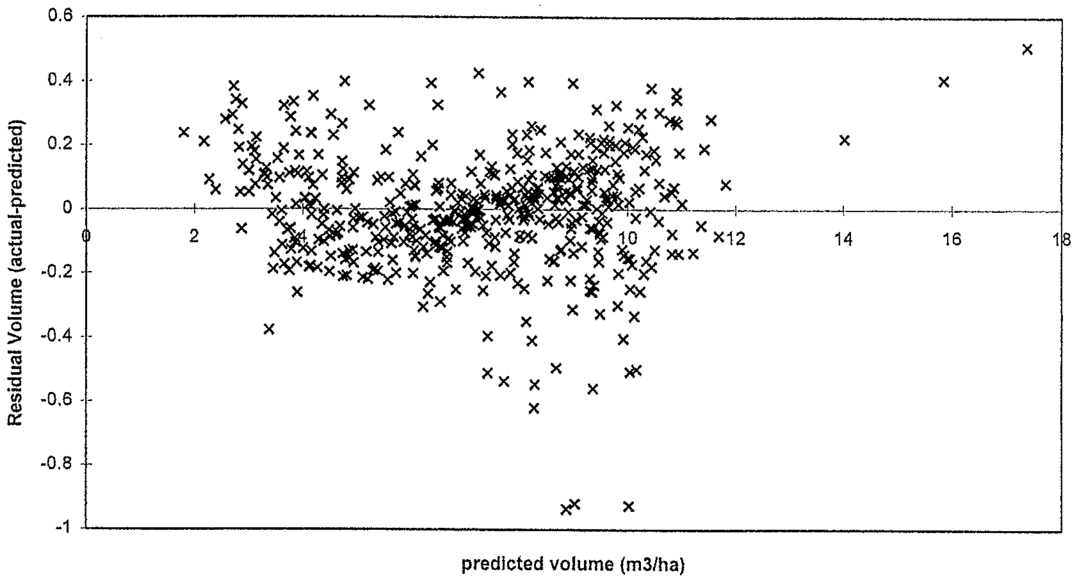

Figure 14- Residuals

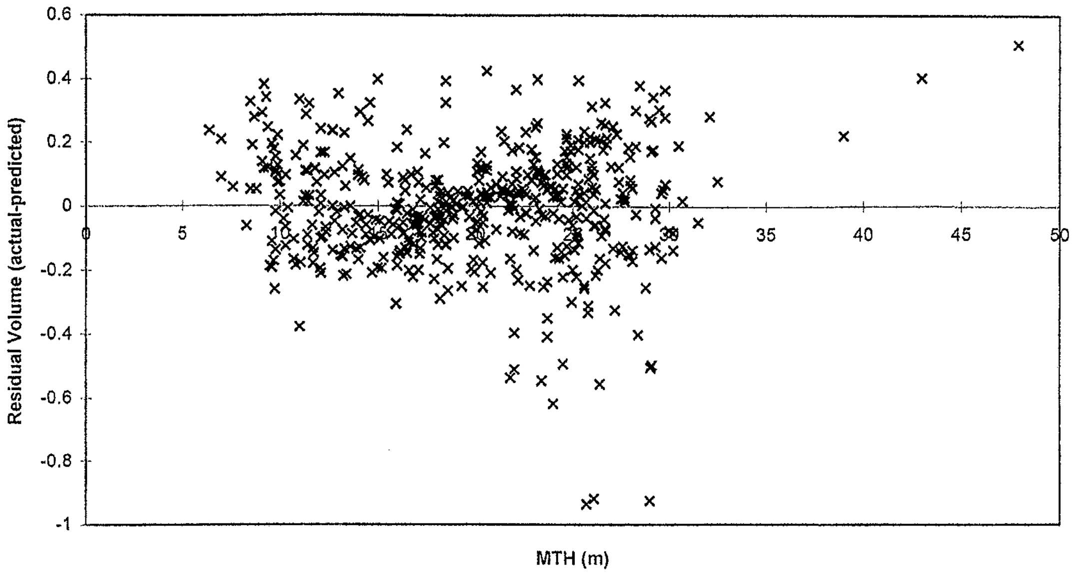

Figure 15- Volume residuals v mean top height

VALIDATION

Comparison with Hayward model

In developing a new model for *E. regnans* it is useful to be able to compare the results given with the existing model to see what, if any improvements have been made. To this end the NZFP model based on data from the Kinleith region of the Central North Island, and the new *E. regnans* model were compared in terms of mean top height, basal area, and stand volume prediction.

The form of the equations for the Hayward model for mean top height, basal area and stand volume are detailed below and follow the methodology described by Clutter *et. al.* (1983).

Height

The Hayward height model was used to predict mean top height for data held in the nationwide *E. regnans* database using the original coefficients (Equation 11).

$$\ln(H_2) = \ln(H_1) \times \left(\frac{T1}{T2}\right)^a + b \times (1 - \left(\frac{T1}{T2}\right)^a) \qquad \textbf{....(11)}$$

Where **H_1** = Plot mean top height (m) at age T_1 (years)
H_2 = Plot mean top height (m) at age T_2 (years)

a = 0.5356
b = 4.7541

Table 5- Comparison of height residuals

	Hayward	MacLean & Lawrence[3]
Max	2.5	2.3
Min	-2.7	-2.2
Range	5.3	4.5
Mean	-0.16	0.09
Sum	-121.1	65.8
RMS[4]	0.72	0.48

A comparison of the height model residuals in Table 5 shows that the MacLean and Lawrence model is the better predictor of height, with less bias and variability.

Basal area

The Hayward function (12) was applied to the nationwide *E. regnans* database using the original coefficients. The function was then compared with the new model. The results are presented in Table 6.

$$\ln(B_2) = \ln(B_1) \times \left(\tfrac{T1}{T2}\right) + a \times (1 - \left(\tfrac{T1}{T2}\right)) + b \times N \times (1 - \left(\tfrac{T1}{T2}\right)) \qquad ....(12)$$

Where $\mathbf{B_1}$ = basal area (m^2/ha) at age T1 (years)
$\mathbf{B_2}$ = basal area (m^2/ha) at age T2 (years)
N = initial stocking (stems/ha)

a = 4.5352
b = -0.0000937

Table 6- Comparison of basal area residuals

	Hayward	MacLean & Lawrence
Max	7.09	4.65
Min	-2.87	-3.94
Range	9.96	8.59
Mean	-0.37	-0.03
Sum	-242.79	-20.71
RMS	1.055	0.853

Analysis of residuals from both the original and re-estimated Hayward models indicates a strong bias, with increasing under-prediction of basal area as age increases.

The new model (MacLean and Lawrence), with the incorporation of the basal area bias correction, exhibits less bias and variability and is a better fit overall.

[3] Equation (2) derived as per Garcia (1979, 1984)

[4]RMS: Residual Mean Square is $\sqrt{\frac{\Sigma(residual^2)}{n}}$ where n is the number of observations

Stand volume

The form of the Hayward volume function is:

$$V = a \times B \times H + c \qquad \text{....(13)}$$

Where: **B**= basal area (m^2/ha)
H= mean top height (m)

a = 0.3558
b = -1.449

The new model has resulted in a significant improvement over the Hayward model. The mean residual has been greatly reduced and residuals are more evenly distributed around zero (Table 7).

Table 7- Comparison of stand volume residuals

	Hayward	**MacLean & Lawrence**
Min	-32.6	-25.9
Max	40.3	23.8
Range	73.0	49.7
Mean	2.5	0.1
Sum	1228.0	58.2
RMS	6.2	3.5

Limitations of the Hayward model

The Hayward model lacks a mortality function and does not adequately account for changes in stocking over time. *E. regnans* is not sufficiently healthy to fully support this assumption and as a result, volume and basal area predictions based on the Hayward model may be overestimated.

Secondly, the Hayward model does not attempt to model thinnings, which limits its use for solidwood regimes incorporating one or more thinnings to ensure an adequate final crop of relatively uniform size and form.

In summary, the Hayward model was developed using data from a limited geographical area (the Kinleith region), and was never expected to model growth elsewhere in New Zealand. This has been confirmed in the comparison exercise with the new model.

Regime analyses

Current silvicultural regimes tend to favour harvesting *E. regnans* at less than 20 years for pulp. Some preliminary work has been undertaken to assess the solidwood potential for young (age 22) *E. regnans* (Somerville *et al* 1997).

Two possible silvicultural regimes were evaluated at two hypothetical site qualities and the results compared with the available data. While the regimes are not fully representative of those found in the database, they indicate possible future scenarios.

Table 8- Regime descriptions

Regime	Site Index	Starting Stocking	Age thinned- 600 sph	Age thinned - 200 sph
Sawlog1	36	1100	4	8
Pulp1	36	1100	4	
Sawlog2	40	1100	3	8
Pulp2	40	1100	3	

The height model can be seen to be a good predictor of height growth, as shown in Figure 16.

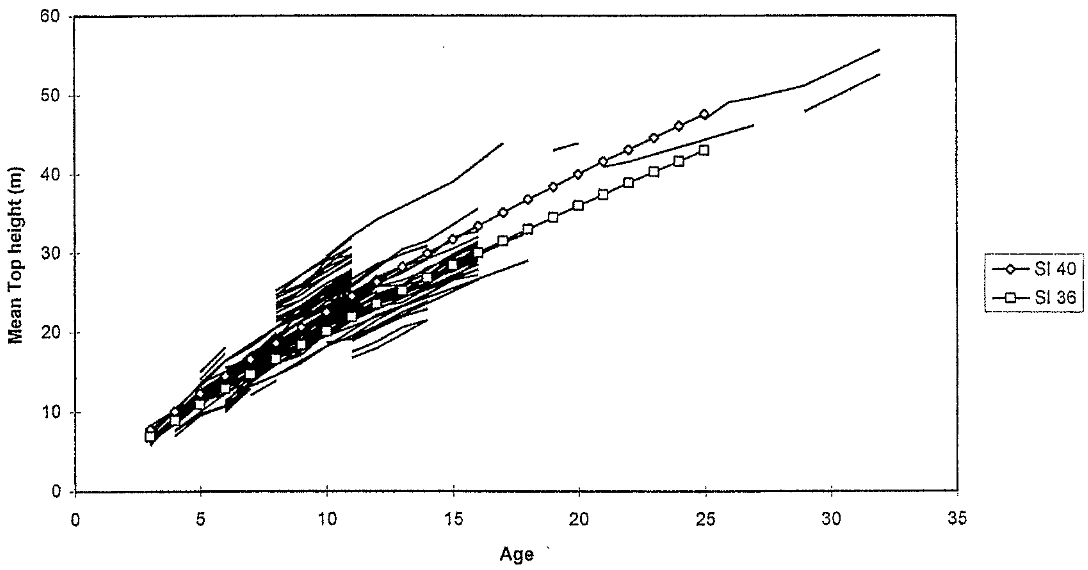

Figure 16- Mean top height v age

Although predicted basal areas for the prescribed regimes fall well within the range of the actual data (Figure 17), the large amount of variation in the data makes it difficult to draw definitive conclusions for all regimes.

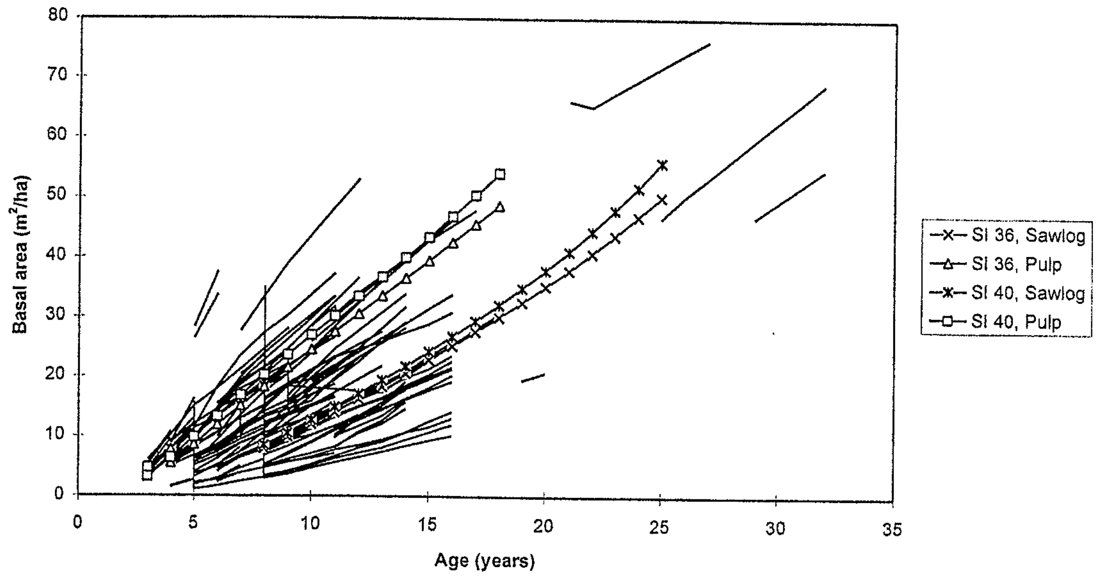

Figure 17- Basal area v age

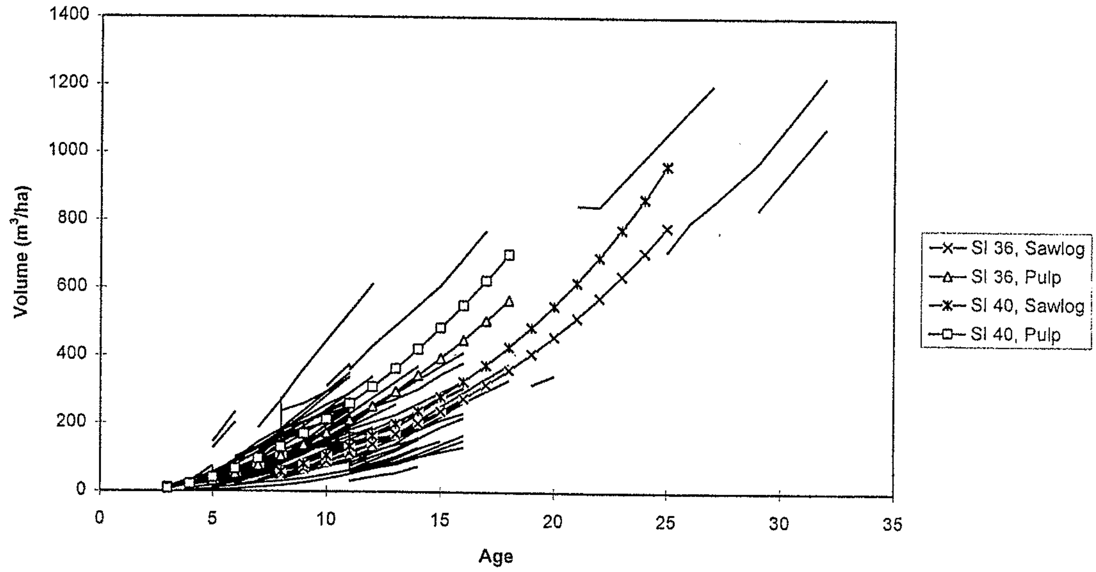

Figure 18- Volume v age

The volume function provides good estimates up to the age of 20. However predictions for older ages appear to be less reliable.
The new growth model is a good predictor of growth for both regimes and sites up to age 20 years. Height, basal area and volume predictions are well within the bounds set by the data, and the trends are consistent with those in the data. At high site indices (greater than 40m) and older ages (greater than 20 years for high site indices and 25 years for lower sites) care must be taken. In these situations both stand volume and basal area predictions appear to be overpredicted.

CONCLUSIONS

Due to the very restricted range of the dataset, the integrity of the predictive functions, particularly those for basal area and stand volume, appears to be compromised beyond age 30 years. However there is currently little interest from the forest industry in general, and the Management of Eucalypts Co-operative in particular, in developing more than a basic model and further improvements are unlikely until more extensive data become available.

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