Indicative growth and yield models for stringybark eucalypt plantations in northern New Zealand

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Abstract

Demand for growth and yield information prompted development of predictive models using very limited data collected from even-aged *Eucalyptus eugenoides* Sieb. ex Spreng., *E. globoidea* Blakely, *E. muelleriana* Howitt, and *E. pilularis* Smith plantations around northern New Zealand. The models can be used in combination to obtain indicative predictions of height growth, total standing volume yield, average tree size, and log grade recovery based on inputs of site index or height-age data and stand density (stocking). Results indicated that volume yield was strongly influenced by stocking and site quality. Site index estimates for the 35 sample plots ranged from 12.5 m to 32.6 m mean top height at base age 15 years. Most volume yield predictions were within 25% of actual yields and average diameter predictions within 20% of actual data. Sawlog grade recovery was found to increase with average tree size, but varied widely between the small number of stands sampled.

Introduction

Forest growth and yield information has a variety of important applications including forest valuation, carbon modelling, timber and log supply forecasting, investment decision-making and design of silvicultural regimes. Total standing volume predictions are useful for above-ground carbon or biomass estimation. However, total standing volume can include a significant volume of residues and cutting waste. Residues consist mainly of stumps, forks, and breakage, whereas cutting wastes are portions of stem lost during log-making for optimal solidwood grade recovery. Predictions of residue volume can be subtracted from total standing volume to obtain estimates of whole-tree 'fibre' volume. Cutting waste may be included within the fibre volume when whole trees or long logs are extracted for pulping, and should therefore be predicted separately. Predictions of volume recovery by log grade are useful when performing economic analyses of forestry investments and designing plantation management regimes. This article presents models that summarise available stand growth and yield data for *E. eugenoides*, *E. globoidea*, *E. muelleriana*, and *E. pilularis* (collectively termed "stringybark eucalypt") stands in northern New Zealand. The models can be used in combination to provide indicative estimates of mean top height growth, total standing volume yield, and average tree diameter, and to divide total standing volume into sawlog and pulp log grades, residues and cutting waste.

Methods

Temporary inventory plots were established in many of the known stands, and MARVL (Method of Assessing Recoverable Volume by Log-types) assessment of the trees was undertaken (Deadman & Goulding 1979). These data complement successive measurement data collected from permanent sample plots (Pilaar & Dunlop 1990) within managed stands (Table 1). The stringybark eucalypt data were analysed following methods used by Berrill & Hay (2005) to model *E. fastigata* stand growth and yield. Mean top height and diameter were defined as the average height and diameter at breast height 1.4 m (dbh) of the 100 largest-diameter trees per hectare, respectively. Average tree diameter was defined as quadratic mean diameter, the dbh of average tree basal area. Total standing volume per hectare was calculated as the sum of individual tree volumes (inside bark) predicted by tree volume equations (Gordon. *et al*. 1999). Height growth, volume yield, and average tree diameter functions were fitted to data summarised in Table 2 through non-linear least squares and multiple linear regression. Site index, defined as mean top height at base age 15 years, was predicted for each plot and summarised by species and geographic region. Graphs were produced to demonstrate height growth, volume yield and tree size predictions across the range of data used to develop each model. Log grade recovery models were fitted to MARVL data converted to percentages of total standing volume after combining poorly represented grades into either sawlog or pulp log grades, cutting waste, and residues. Model goodness-of-fit was described in terms of RMSE, the square root of the mean of squared prediction errors. The RMSE values represent the average prediction error for all available data.

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Results

Height growth

Site index curves that encompass the range of available data (Fig. 1; Table 3) were created using a polymorphic Chapman-Richards (Richards, 1959) difference equation that predicts mean top height H_2 at age T_2 dependent on starting values of mean top height H_1 and age T_1 (Equation 1).

$$H_2 = a\left[1-\left(1-\left(\frac{H_1}{a}\right)^{\left(\frac{1}{c}\right)}\right)^{\left(\frac{T_2}{T_1}\right)}\right]^c \qquad (1)$$

The model was fitted in difference form with the asymptote parameter fixed (a=55); the fitted parameter estimate was c = 1.3659 ($RMSE$ = 1.1).

Volume yield and tree size

Multiple linear regression models were used to describe relationships between the natural logarithm of total standing volume yield, average tree diameter, stocking, and mean top height. Data from stands below age 5 years (n=23 measurements) and above 1500 stems/ha (n=3) were excluded from analyses of volume yield and tree size. The multiple linear regression equations were rearranged to predict total standing volume yield or average tree diameter (Y) for stands aged 6-36 years as a function of mean top height H and stocking N (Equation 2).

$$Y = ea+b^{In(H)+c\,In(N)} \qquad (2)$$

Parameter estimates were

Volume (m3/ha)	a = -5.37875	b = 2.30377	c = 0.54681	(RMSE = 170)
Mean dbh (cm)	a = 2.34135	b = 0.74639	c = -0.21992	(RMSE = 4.7)

Volume yield and average tree diameter predictions for a range of stockings as a function of mean top height are shown in Fig. 2. Graphs of model predictions have axes and curves restricted within the approximate range of values in the dataset: max. age 36 years; 100-1500 stems/ha; 12.5-30 m site index; max. total standing volume 1160 m^3/ha, excluding one plot measurement at age 60 years: 650 stems/ha; 51.8 m mean top height; 2100 m^3/ha total standing volume.

Log grade recovery

A linear model was used to describe the relationship between average tree diameter D and percentage sawlog recovery S (Equation 3).

$$S = a + bD \qquad (3)$$

Parameter estimates were a = 9.80158 and b = 0.55018 ($RMSE$ = 12.8).

Generalized logistic functions were used to describe relationships between average tree diameter D and percentage pulp recovery Y - where pulp recovery was defined as the sum of percentage sawlog and pulp recovery, and between average tree diameter and percentage cutting

Table 1: Permanent sample plot (PSP) and MARVL sample plot count, age statistics for measurement data, and maximum volume MAI by species and geographic region.

Region	Species	No. PSP	No. MARVL	Mean age (years)	Min. age (years)	Max. age (years)	Max MAI (m^3/ha)
Northland	*E.pilularis*	9	1	8.4	3	60	35.4
	E.pilularis	9	1	8.4	3	60	35.4
	E.globoidea	4		8.4	3	6	6.3
Coromandel & Bay of Plenty	*E.pilularis*		3	35.3	35	36	11.8
	E.muelleriana		8	35.4	35	36	33.2
	*E.globoidea**		4	36.0	36	36	18.8
All data		19	16	14.5	2.8	60	35.4

*includes *E. eugenoides* which has similar taxonomy.

Table 2: Combined permanent sample plot and MARVL dataset summary (n=56).

	Age (years)	Stocking (stems/ha)	Mean top diameter (cm)	Mean top height (m)	Basal area (m^2/ha)	Volume (m^3/ha)	Volume MAI (m^3/ha)
Mean	14.5	808	27.8	15.8	25.7	212.8	7.0
s.d.	15.0	670	24.9	13.7	40.9	407.4	9.2
min.	2.8	72	2.4	3.0	0.1	0.2	0.1
max.	60.0	3609	109.7	51.8	211.0	2122.9	35.4

Table 3: Site index (mean top height at age 15) summary statistics by species and region.

Region	Species	Total no. plots	Average site index (m)	s.d. (m)	Min. (m)	Max. (m)
	E.pilularis	10	25.2	4.8	18.8	32.6
Northland	*E.pilularis*	6	22.4	3.2	17.6	27.6
	E.globoidea	4	3.8	3.8	21.1	29.3
Coromandel & Bay of Plenty	*E.pilularis*	3	16.6	16.0	16.0	17.5
	E.muelleriana	8	17.9	15.6	15.6	19.6
	*E.globoidea**	4	14.1	12.5	12.5	14.8
All data		35	20.9	5.0	12.5	32.6

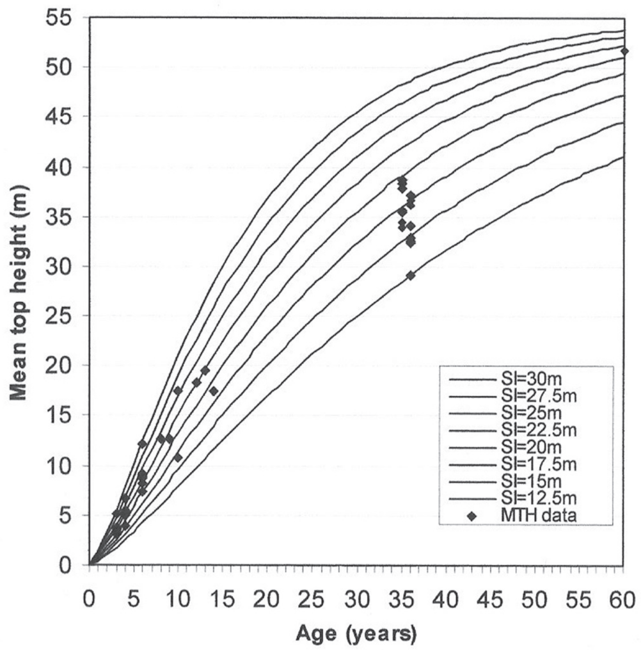
waste Y - defined as the sum of percentage pulp recovery and cutting waste (Equation 4).

$$Y = \frac{a}{1 + e^{b-cD}} \qquad (4)$$

Pulp recovery	a=95.3764	b-1.4457	c=0.1148	(RMSE=2.9)
Cut waste	a=99.5120	b=0.7403	c=0.0974	(RMSE=2.0)

Predictions indicated that percentage recovery of sawlog grades increases while percentage waste decreases with increasing tree size (Fig. 3).

Figure 1: Site index curves that encompass range of height-age data; site index (SI):12.5-30 m at base age 15 years (n=21 pairs height-age data).



Discussion

The data used for model development were characterised by a low average age (Table 1), high stocking, and low average tree size (Table 2). Differences in MAI data (Table 1) and site index estimates (Table 3) should not be interpreted as differences in overall productivity between species and regions because of the small number of plots. Additionally,

Figure 3: Influence of average tree diameter on predicted log grade recovery as a cumulative percentage of total standing volume (TSV). Example: stand with mean dbh=40 cm has approx. 32% of total standing volume in sawlog grades, 60% pulp logs, 4% cutting waste and 4% residue waste. Predicted sawlog volume expressed as a percentage of total standing volume; pulp log volume and cutting waste expressed as cumulative percentages with preceding (more valuable) grades, as a percentage of total standing volume e.g., cumulative percentage pulp logs = percentage sawlogs + percentage pulp (n=16 MARVL plots).

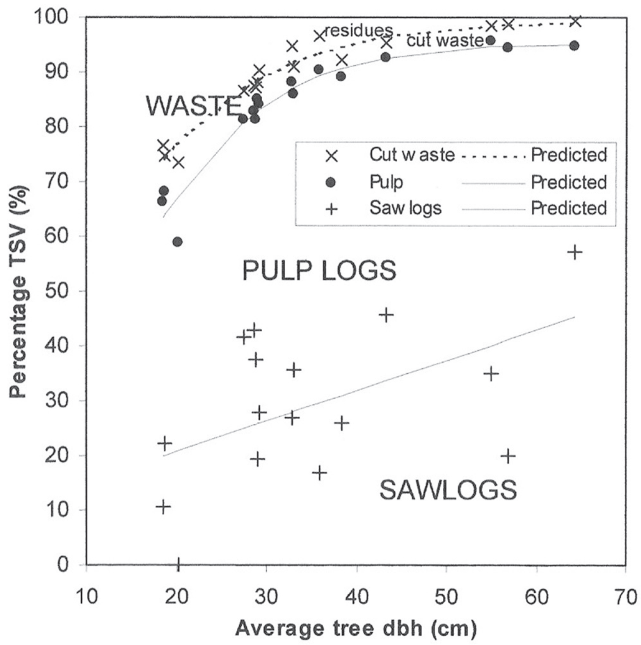
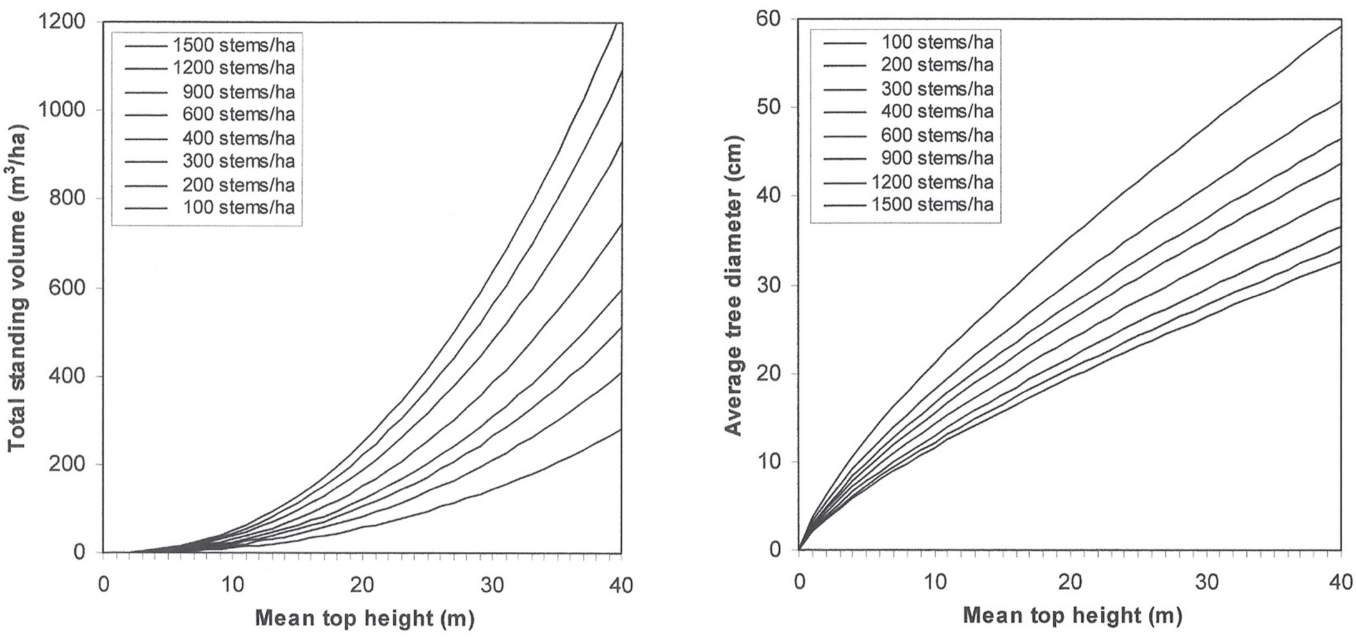


Figure 2: Total standing volume and average tree diameter predictions for a range of stockings 100-1500 stems/ha (n=30).



MAI may not have reached its maximum in younger stands, or in thinned stands. However, the data indicate that growth can vary widely between stands. The inclusion of mean top height as an explanatory variable in the volume yield model should account for some of the variation in volume yield attributed to differences in site quality and species. The height growth model can be used to obtain mean top height estimates for any age based on local height-age data (H_1 at age T_1) or site index data (H_1 at base age T_1=15 years) presented in Table 3 when starting values are limited to stocking and age. The height growth model was developed with data from permanent sample plots measured for four years or less, with stand age at the time of measurement ranging from 3-17 years. Too few data were available to develop a model without fixing the upper asymptote to a value of 55 m that narrowly exceeded the greatest mean top height in the dataset (51.8 m at age 60). Candy (1997) fixed the upper asymptote of a height growth model for *E. nitens* at 60 m, citing lack of data from older stands as justification.

The mean top height, volume yield and tree size models can be used in combination with site index data to assess the influence of stocking and site quality on growth and yield predictions. For example, predictions of total standing volume indicated that stands on sites of average (site index 21 m) and high quality (site index 30 m) would produce approximately 500 m^3/ha and 800 m^3/ha total standing volumes, respectively, for 400 stems/ha at age 30. On the same sites, 600 stems/ha are predicted to yield approximately 600 m^3/ha and 1000 m^3/ha at age 30 while sacrificing less than 5 cm average tree diameter. Since mortality was not predicted, higher initial stockings may be needed to achieve the predicted yield for a given stocking at harvest. Competition-induced mortality can be estimated by defining an upper limit to tree size and stocking data in the form of a stand density index (SDI) (Reineke, 1933). Tree size and stocking data showed that nine plots exceeded the upper limit of SDI=500 for *E. globulus* reported by Reineke (1933), of which six plots had SDIs over 700 and three plots above SDI=900. The oldest plot (age 60) exceeded SDI=1000, the upper limit of growing space occupancy reported for second growth *Sequoia sempervirens* in California: log(N) = -1.605 log(D)+13, where N = stocking (stems/ha); D = average diameter (cm). This approximate upper limit could be used to constrain volume growth and yield projections for a given stocking within realistic biological limits. Most volume yield predictions were within 25% of actual yields and average diameter predictions within 20% of actual data. Model RMSE values show that the average prediction errors for volume yield and average tree diameter were 170 m^3/ha and 4.7 cm respectively.

The MARVL sampling was opportunistic in that it included most known, accessible stands suitable for MARVL assessment. Log grade recovery data and models indicate that recovery of sawlog grades increases with average tree size (Fig. 3). For example, the approximate percentage recovery of sawlogs increases from approximately 32% to 42% of total standing volume in stands with mean diameters of 40 cm and 60 cm respectively. Results also indicate that waste can account for a significant portion of total standing volume in stands with low average tree size (Fig. 3). Sawlog grade recovery was highly variable, implying that too few data were available to develop a reliable model and that other factors not considered here such as management regime (i.e. timing and intensity of thinning) have an important influence on sawlog recovery.

Summary

The simple yield modelling approach adopted here circumvents the need for basal area, mortality, and thinning models by using height growth and volume yield models to predict total standing volume development, and height growth and stocking data to obtain average tree diameter estimates from a separate model. Linear and logistic models described the relationship between average tree size and log grade recovery. Data and yield model predictions indicate that stringybark eucalypt stand growth can vary widely between sites and is strongly influenced by stocking across the range of available data. The data available for model development were extremely limited therefore model predictions should be regarded only as indicative until validated with independent data.

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