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STATIC STAND AND TREE CHARACTERISTICS MODELS FOR *ACACIA MANGIUM* PLANTATIONS

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FORSS, E., MALTAMO, M. & SARAMÄKI, J. 1998. Static stand and tree characteristics models for *Acacia mangium* plantations. A method and models to calculate stand characteristics, for example in forest inventory applications, are presented for plantations of *Acacia mangium*. The method consists of four parts: equations for estimating the parameters of the diameter distribution function (Weibull) and individual tree height, total tree volume and utilisable stem volume. The parameters of the diameter distribution function and of the general tree height model are derived from stand variables which are quick to assess in a forest inventory. Total volume estimation is based on tree diameter and height, and utilisable volume estimation is based on tree diameter and a variable top diameter limit for pulpwood. The diameter distribution and height models are based on mainly remeasured data on 62 semipermanent and permanent plots (1.0 to 7.4 y of age) in South Kalimantan, Indonesia. The accuracy of the model chain is tested using the bias and root mean square error of the predicted stand volume as criteria.

Key words: *Acacia mangium* - forest inventory - diameter distribution - Weibull - volume equation - general tree height model

FORSS, E., MALTAMO, M. & SARAMÄKI, J. 1998. Model dirian statik dan ciri-ciri pokok di ladang *Acacia mangium*. Satu kaedah dan model untuk mengira ciri-ciri dirian, contohnya dalam amalan inventori hutan, diberikan kepada ladang *Acacia mangium*. Kaedah ini mengandungi empat bahagian: persamaan untuk menganggarkan parameter fungsi taburan diameter (Weibull) dan ketinggian setiap pokok, jumlah isipadu pokok dan penggunaan isipadu batang. Parameter fungsi taburan diameter dan model ketinggian setiap pokok secara umum diperoleh daripada pemboleh ubah dirian yang dapat ditaksirkan dengan cepat dalam inventori hutan. Anggaran jumlah isipadu adalah berdasarkan kepada diameter dan ketinggian pokok, manakala anggaran kebolehgunaan isipadu berdasarkan kepada diameter pokok dan pemboleh ubah had diameter hujung bagi kayu pulpa. Model taburan diameter dan ketinggian sebahagian besarnya berdasarkan kepada data yang diukur semula bagi 62 plot separa kekal dan plot kekal (berumur 1.0 hingga 7.4 tahun) di Kalimantan Selatan, Indonesia. Ketepatan rangkaian model ini diuji menggunakan kriteria ralat min kuasa dua pincang dan akar isipadu dirian yang diramalkan.

parts: parameter models for the diameter distribution and individual tree height are derived using commonly measured stand variables. Total tree volume and utilisable volume are predicted using tree diameter, tree height and a top diameter limit for pulpwood. For comparison, a standwise volume model is also presented. The accuracy of these different models is tested using the bias and root mean square error (RMSE) of the predicted stand volumes in the modelling data. The models are also tested with data from some thinned plots which were not used in the development of the models.

Materials and methods

The data were collected in the trial plantations of *A. mangium* of the Indonesian-Finnish Reforestation and Tropical Forest Management Project (ATA-267) in South Kalimantan, Indonesia. The plantations are situated in Riam Kiwa (3° 30'S, 115° 20'E), in Riam Kanan (3° 50'S, 115° 10'E) and on the island of Pulau Laut (3° 60'S, 116° 20'E) on sites earlier occupied by *I. cylindrica*. The annual rainfall in Riam Kiwa is 2514 mm (Taylor 1991).

For the estimation of the diameter distributions and the stand height curves, 39 semipermanent unthinned yield study plots were available. The stands had been established with the commonly used spacings of 2 × 4 m (1250 planting spots ha^{-1}) and 3 × 3 m (1111 planting spots ha^{-1}) with seed collected in Subanjeriji, South Sumatera. In addition, data from a spacing trial with 23 plots were available. The spacing trial had been established with seed collected in Papua New Guinea (seedlot 17872, CSIRO) and included planting densities ranging from 1.5 × 1.5 m to 6 × 6 m. Further 6 thinned plots were available for model tests. These plots had been established with a spacing of 2 × 4 m, thinned at the age of 4.3 y, and measured at the ages of 4.3, 5.2 and 7.4 y. Because of the common multistems, the number of stems per hectare varied widely. The plot size varied between 10 × 10 m and 8 × 10 m for the yield plots and was 7 × 7 m for the spacing trial.

The measurement data were collected between March 1991 and February 1995. The plots were measured for diameter on each tree. In the yield plots height was measured systematically on every fourth tree, with additional measurements on the largest trees unless they fell within the systematic sample. In the spacing trial, the height of every second tree was measured. Some of the yield plots could only be measured once or twice because the plots had been destroyed by fire. The spacing trial and 19 of the yield plots, including the thinned plots, were measured three times but 15 of the yield plots were only measured once. The ages of the study plots (2.5 to 7.4 y in the yield plots and 1.0 to 3.1 y in the spacing trial) almost cover the expected rotation of less than 10 y. The range of data is presented in Table 1.

The choice of a theoretical distribution for describing the diameter distribution has been widely discussed (e.g. Borders *et al.* 1987, von Gadow 1987, Maltamo *et al.* 1995.). The Weibull distribution has proven to fit well in most studies. Furthermore, the Weibull distribution is flexible and easy to apply (Bailey & Dell

Introduction

Acacia mangium Willd., originally from Queensland (Australia), Papua New Guinea and East Indonesia, has become a major plantation species in Malaysia and Indonesia (Halenda 1988, RAPA 1988, Hadi *et al.* 1990, Groome 1991, Lim 1991, Mohamad Lokmal & Ab. Rasip 1991). It was first introduced to Sabah, Malaysia, in the late sixties and plantations were established in the late seventies (Pinyopusarerk *et al.* 1993). *Acacia mangium* has also been introduced to several other countries in the continental and insular South Asia, Central America and Africa (CATIE 1992, Pinyopusarerk *et al.* 1993).

The popularity of the species is based on its ability to successfully compete with the vigorous alang-alang grass, *Imperata cylindrica* (Weinland 1987, Sipayung 1988, Hadi *et al.* 1990). In Indonesia alone there are roughly 20 million hectares occupied by alang-alang (JOFCA 1990). These areas regenerate naturally very slowly because of the heavy competition by the grass (Soerianegara 1976). Establishment of plantations with pines and eucalypts would be very costly and difficult (Golokin & Cassels 1989, Hadi & Ådjers 1990, Hadi *et al.* 1990, Lazuardi & Mikkilä 1991). *Acacia mangium* grows well even in acid and badly eroded soils (RAPA 1988, Tan 1991). It fixes atmospheric nitrogen and produces a rich harvest of litter, which improves the physical and chemical properties of the soil (Halenda 1988, RAPA 1988, Ang & Muda 1991, Miller & Hepburn 1991, Hansawi & Jugah 1991).

The wood of *A. mangium* is well suited for pulp and particleboard (Logan 1987, RAPA 1988, RAPA 1990, Chew *et al.* 1991, Fåhrdeus 1991, Groome 1991, Prawirohatmodjo 1991, Razali & Kuo 1991, Salleh & Wong 1991). Production of sawn timber and plywood is handicapped by the technical quality of the stems, which are often forked, branchy, crooked (Chan 1986, Weinland 1987, Mead & Speechly 1991, Prawirohatmodjo 1991) and have heart rot (Lee *et al.* 1988, RAPA 1990, Mahmud *et al.* 1993).

For forest management purposes, it is essential to know the state and amount of timber in the forests which have been designated for supplying wood for the forest industries. Furthermore, in pulpwood production the size distribution of the trees is important in selecting the appropriate harvest method. In forest inventories, only some stand variables, e.g. mean diameter and number of stems per hectare, are measured. Then stand characteristics, e.g. total volume, can be predicted in two ways. Firstly, it is possible to use standwise volume models to predict stand volume directly from stand variables (Vuokila 1965). Secondly, it is possible to use the diameter distribution approach. In the latter case, the parameters of a theoretical diameter distribution are predicted using known stand variables. Then the distribution is formed and treewise models are used to calculate tree heights and volumes (Bailey & Dell 1973). The advantage of the diameter distribution approach is that instead of the whole stand, a part of the distribution, e.g. sawn timber, can be considered.

In this paper, models are presented for calculating different stand volume characteristics for forest inventory purposes. The model chain consists of different

1973). In this study, the diameter distributions were estimated using the two-parameter approach of the Weibull distribution. The probability density function of the two-parameter Weibull distribution for a random variable x is

$$f(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} \exp\left(-\left(\frac{x}{b}\right)^{c}\right) \text{ for } x>0 \qquad (1)$$

where b is the scale parameter and c is the shape parameter. The cumulative distribution function for Weibull is also known; it is easy to define the number of trees with a certain diameter (Bailey & Dell 1973). The cumulative distribution function is

$$F(x) = 1 - \exp\left(-\left(\frac{x}{b}\right)^{c}\right. \qquad (2)$$

The maximum likelihood estimates of the parameters were obtained by maximising the natural logarithm of the likelihood function of the Weibull function (Rennolls *et al.* 1985). Such estimation was obtained using the IMSL library (Anonymous 1984).

To obtain a height estimate for each tree in a stand, the diameter-height equation developed by Michailoff (1943) was fitted to each plot and measurement. The equation has the form

$$h = 1.3 + \beta_0 e^{\frac{-\beta_1}{d}} \qquad (3)$$

where h = total tree height (m)
d = dbh (cm)
β_0, β_1 = coefficients

Equation 3 has several desirable properties as a height-age curve (see Gaffrey 1988, Sloboda *et al.* 1993): it is simple as it has only two parameters, it has the value 1.3 when diameter is zero and approaches an asymptote as diameter increases, and it is flexible enough to fit the data well.

After the diameter distributions and height curves were estimated, parameters of these functions were regressed using known stand characteristics in order to obtain generally applicable models. A mixed model with a random time-effect was assumed. The measurements from a certain plot at different times were assumed to be correlated. In these models the generalised least square (GLS) method was used. The GLS method divides the residual variation of the model into between and within variation of the plots and the covariance structure of the material is taken into account in the parameter estimates (Lappi 1986). Also the stand volume model was fitted using the GLS technique.

The data for modelling total and merchantable tree volume consisted of 126 felled trees from 12 stands in South Kalimantan and South Sumatra, on which diameters were measured along the whole stem (Table 2). The data are the same as in the work of Sadono and Setyarso (1992), but with additional 25 big trees measured in an old provenance trial in Riam Kiwa. All sample trees originated from seeds collected in Subanjeriji. Total volume, as well as utilisable volume up to top diameters of 5 and 10 cm, was calculated using cubic spline interpolation. Measurement errors and possible oscillations of the spline were corrected with the help of graphical output on the screen (Saborowski 1982). Both volumes were calculated assuming a constant stump height of 10 cm (mean stump height was 10.1 cm), as there seemed to be no relationship between stump height and diameter at breast height in the sample trees. The volume equations developed by Wan Razali *et al.* (1989) and Sadono and Setyarso (1992) were not adopted, as in the former the equation was developed to estimate the volume up to the fixed merchantability limit of 10 cm, and the latter was based on tree diameter only. All regression models were fitted using SAS statistical software.

Table 1. General description of the data for the diameter distribution model and the general tree height model (n=145)

	A	N	d_m	h_m	d_{dom}	h_{dom}	V
Min	1.0	352	1.8	2.2	2.8	3.1	0.3
Max	7.4	4989	18.3	23.6	26.8	26.7	286.1
Mean	3.7	1516	9.4	11.3	14.7	13.5	86.2

Note: A = stand age (y); N = stems ha^{-1}; d_m = arithmetic mean diameter (cm); h_m = arithmetic mean height (m); d_{dom} = diameter of the dominant trees (cm); h_{dom} = dominant height (m), height of the arithmetic mean stem of the 100 thickest stems ha^{-1}; V = stand volume (m^3 ha^{-1}).

Table 2. General description of the data from felled trees for the volume equation (n=126)

	d (cm)	h (m)	v (m^3)
Min	4.4	7.2	0.007
Max	28.3	29.9	0.789
Mean	17.5	18.4	0.238

Results

Diameter distribution

The two-parameter approach of the Weibull distribution was fitted to the empirical diameter distribution separately on each plot and measurement. An example of the development of estimated diameter distribution in one of the plots is presented in Figure 1.

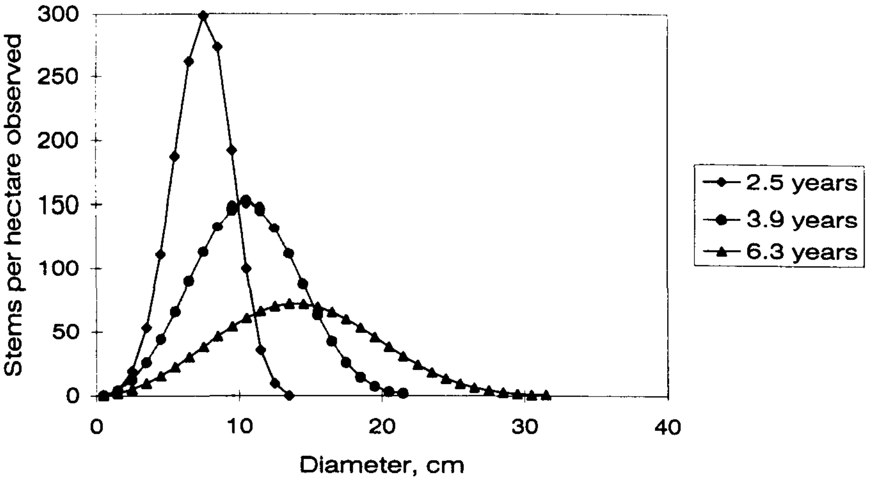

Figure 1. The development of diameter distribution in one stand

The correlation between the estimated parameter *b* and the arithmetic mean diameter in the stand is almost linear (Figure 2). The range in the estimated parameter *c* was from 2.04 to 7.36, the average being 4.11. In the case of the parameter *c*, the strongest correlation was found between the parameter and stand age (Figure 3). Figures 2 and 3 show also the thinned plots which were not used in developing the models. In Figure 3, the development of the parameter *c* in the thinned plots over time can be clearly distinguished.

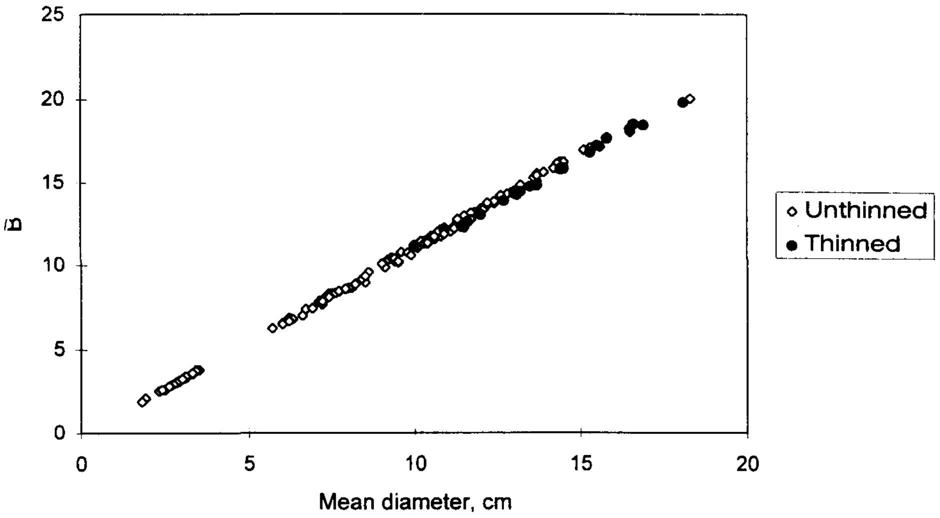

Figure 2. The correlation between mean diameter of the stand and estimated Weibull parameter *c*

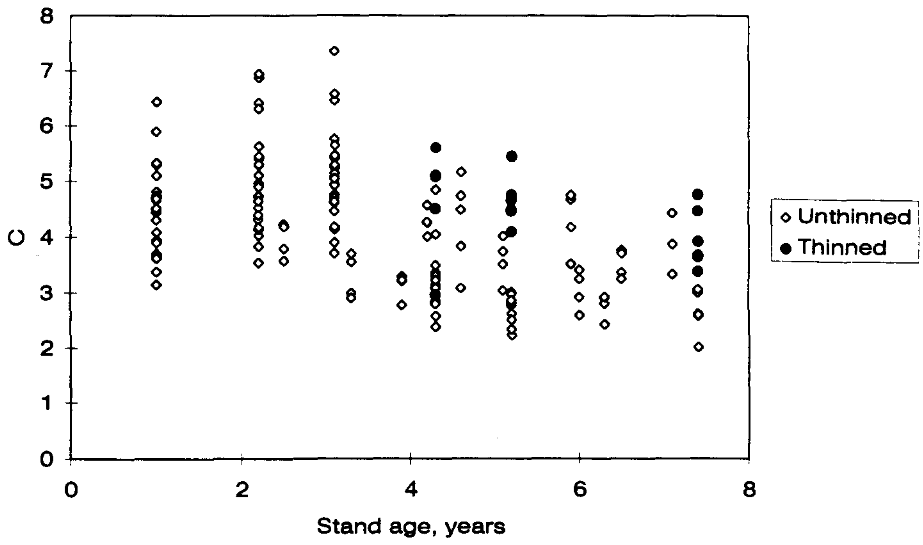

Figure 3. The correlation between stand age and estimated Weibull parameter *c*

The regression models for the parameters *b* and *c* are as follows:

$$b = \beta_{00} + \beta_{01} d_m + \beta_{02} A \qquad (4)$$

$$\ln(c) = \beta_{10} + \beta_{11} A \qquad (5)$$

where d_m = mean dbh (cm)
A = age of the stand
$\beta_{00} .. \beta_{02}$ = coefficients
$\beta_{10} .. \beta_{11}$ = coefficients

The coefficients (and their *t*-values) are

β_{00} = 0.00378 (0.14)
β_{01} = 1.06688 (256.85)
β_{02} = 0.09209 (9.38)
β_{10} = 1.49093 (33.72)
β_{11} = - 0.03053 (3.52)

and the errors of prediction in the models are

RMSE (b) = 0.0659 and RMSE ($\ln(c)$) = 0.1171 (n = 145).

In Equation 5, a correction factor ($\text{RMSE}^2/2$) due to logarithmic transformations was added to the constant term (Meyer 1941) for predictions. The constant was not statistically significant in Equation 5. However, as there is no biological reason to force the model through the origin, the constant was left in the model.

In application, both the parameters *b* and *c* need not be predicted, because if one of the parameters and the median diameter of the stand are known, the other parameter can be calculated analytically using the following relations (e.g. Kilkki *et al.* 1989):

$$b = \frac{d_m}{- (\text{LN}\ (0.5))^{\frac{1}{c}}} \tag{6}$$

$$c = \frac{\ln\ (-\ (\ln\ (0.5)))}{\ln\ (\frac{d_m}{b})} \tag{7}$$

The above relations are modifications of the cumulative distribution function of Weibull.

General tree height model

In order to obtain a model which is able to predict tree heights in a stand without sampling of tree heights and development of a stand specific height-diameter curve, the parameters of the standwise height-diameter Equation 3 were regressed against stand variables:

$$\beta_0 = \beta_{00} + \beta_{01} d_m + \beta_{02} h_{dom} \tag{8}$$

$$\beta_1 = \beta_{10} + \beta_{11} d_m + \beta_{12} h_{dom} + \beta_{13} \ln\ (N) \tag{9}$$

where d_m = mean dbh (cm)
h_{dom} = dominant height (m)
N = number of stems per hectare
$\beta_{00} .. \beta_{02}$ = coefficients
$\beta_{10} .. \beta_{13}$ = coefficients

The coefficients (and their *t*-values) are

β_{00} = - 0.59290 (-1.74)
β_{01} = - 0.31894 (-4.44)
β_{02} = 1.48904 (32.47)
β_{10} = 6.77843 (4.67)
β_{11} = - 0.13929 (-2.41)
β_{12} = 0.29710 (8.43)
β_{13} = - 0.72857 (-3.75)

and the errors of prediction in the models are

$$\text{RMSE}(\beta_0) = 1.1005 \text{ and RMSE}(\beta_1) = 0.8550 \ (n = 145).$$

Dominant height showed the strongest correlation with the parameters of the individual stand height curves. Dominant height describes directly the stage of development of the stand combining the effects of stand age and site quality. The relationship in the data between dominant height and the parameters of the stand height curves are presented in Figures 4 and 5. Also mean diameter was a significant predictor of both β_0 and β_1. Mean diameter and number of stems adjust the model for stand density effects. Figures 4 and 5 show also the thinned plots which were not used in developing the models. Similarly as in Figure 3, the development of the parameters after thinning can be seen. The group of six observations with the smallest dominant heights represents the situation immediately after thinning.

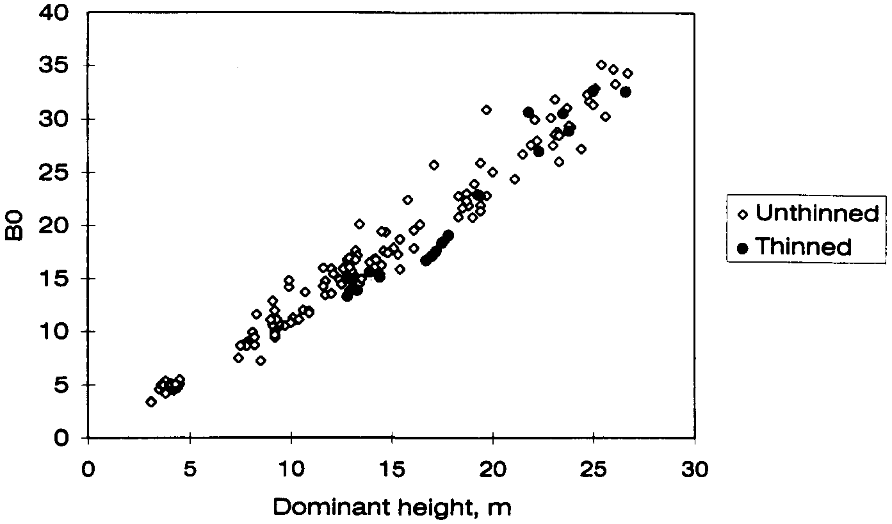

Figure 4. The correlation between dominant height and parameter β_0 of the stand height curves

The relationship between dominant height and the parameters seems to hold also in very young stands which do not yet occupy the site fully (most of the observations from the spacing trial in Figures 4 and 5 with h_{dom} less than 5 m) and in which competition has not yet started to affect the relationships of tree sizes. Stand density logically gains effect on the structure of a stand, and consequently on the parameters of the stand height curves, only after the start of competition.

Thinned stands did not seem to follow the same relationship between dominant height and the parameters one year after thinning. About three years after thinning the stands could not be separated from the unthinned stands any more.

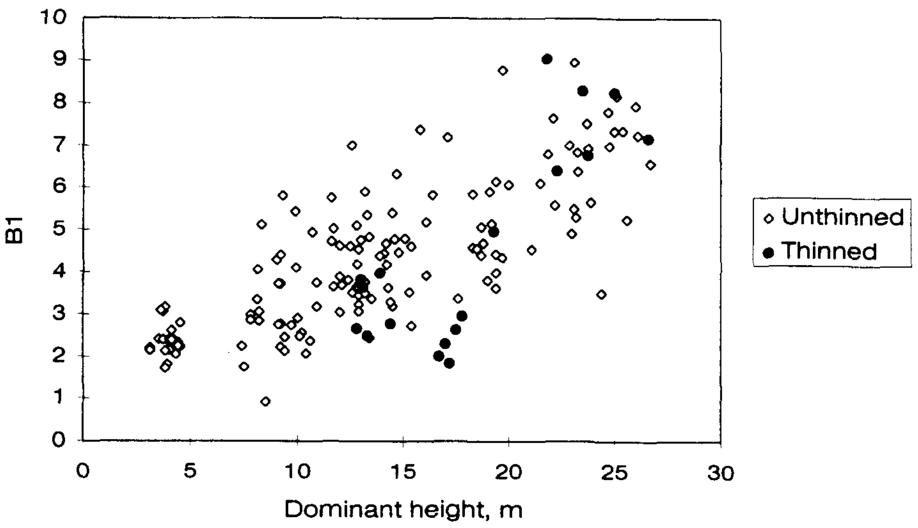

Figure 5. The correlation between dominant height and parameter β_1 of the stand height curves

Tree total volume

Tree total volume (over bark) was modelled with the allometric volume equation (e.g. Crow & Schlaegel 1988). Before fitting the model, a logarithm was taken from both sides of the equation in order to homogenise residual variation. In the equation, volume is estimated as a function of diameter at breast height (dbh) and total tree height:

$$\ln(v) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(h) \tag{10}$$

where v = total tree volume (m^3)
d = dbh (cm)
h = total tree height (m)
$\beta_0..\beta_2$ = coefficients

The coefficients (and their *t*-values) are

β_0 = - 9.83466 (-118.59)
β_1 = 1.70518 (42.68)
β_2 = 1.14496 (19.30)

and the error of prediction in the model is

RMSE ($\ln(v)$) = 0.07818,
RMSE (v) = 0.02296, RMSE(%) = 9.6 (n = 126).

The correction factor due to logarithmic transformation was added to the constant term. Ordinary least squares were used instead of generalised least squares because the residual variation of model between the stands was not significant.

Tree merchantable volume

The merchantable volume of an individual tree (over bark) can be predicted to various top diameter limits with a modification of the stand merchantable volume equation of Amateis *et al.* (1986):

$$v_{m,d} = v e^{\beta_0 \left(\frac{m}{d}\right)^{\beta_1}} \qquad (11)$$

where $v_{m,d}$ = merchantable tree volume (m^3)
v = total tree volume (m^3)
d = dbh (cm)
m = top diameter merchantability limit (cm)

The coefficients (and their standard errors) are

β_0 = - 1.19769 (0.05391)
β_1 = 3.91193 (0.07764)

and the error of prediction in the model is

RMSE = 0.0048, RMSE(%) = 2.0 (n = 241).

Equation 11 is similar to the model of Amateis *et al.* (1986), except for the omission of the part which takes account for the distribution of tree sizes within the stand in the original model. Equation 11 follows an s-shaped curve approaching an asymptote at 1.0, which was obvious in the data both for top diameters of 5 and 10 cm. The model was fitted with non-linear regression using top diameter limits of 5 and 10 cm for each volume sample tree simultaneously. Thus, the model can safely be used to predict stem volume to any top diameter limit between 5 and 10 cm, i.e. pulpwood.

The stand volume model

The stand volume model was estimated for the calculated total stand volume using known stand variables. The model is as follows:

$$\ln(V) = \beta_0 + \beta_1 \ln(d_m) + \beta_2 \ln(h_{dom}) + \beta_3 \ln(N) \qquad (12)$$

where d_m = mean dbh (cm)
h_{dom} = dominant height (m)
N = number of stems per hectare
$\beta_0..\beta_2$ = coefficients

The coefficients (and their *t*-values) are

β_0 = - 10.35227 (164.1)
β_1 = 1.96738 (68.86)
β_2 = 0.94836 (35.03)
β_3 = 1.05196 (118.88)

and the error of prediction in the model is

RMSE(ln(V)) = 0.0476,
RMSE (V) = 4.3, RMSE(%) = 5.0 (n = 145).

The correction factor due to logarithmic transformation was added to the constant term.

The accuracy of different models

In the comparisons the real stand volume was calculated using measured tree diameters, estimated parameters of the height curve (Equation 3) and a tree volume model (Equation 10). The test criteria used in the comparisons were absolute and relative root mean square error (RMSE) and bias. The root mean square error was calculated as follows

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(V_i - \hat{V}_i)^2}{n}} \qquad (13)$$

where V_i is the real volume in stand i, $\hat{V}_i$ is the predicted volume in stand i and n the number of stands.

Correspondingly, the estimate of bias was calculated as follows

$$\text{Bias} = \frac{\sum_{i=1}^{n}(V_i - \hat{V}_i)^2}{n} \qquad (14)$$

The relative values of the test criteria were obtained by dividing the absolute value by the average value of the predicted stand volume.

The methods used in the calculation of stand volume were the following:

Method 1: Estimated parameters of the stand height curve and Weibull function for a given stand. Volume with Equation 10.

Method 2: Predicted parameters of the stand height curve (Equations 8 and 9) and Weibull function (Equations 4 and 5). Volume with Equation 10.

Method 3: Predicted parameters of the stand height curve (Equations 8 and 9) and Weibull parameter *b* (Equation 4), parameter *c* from Equation 7. Volume with Equation 10.

Method 4: Predicted parameters of height curve (Equations 8 and 9) and Weibull parameter *c* (Equation 5), parameter *b* from Equation 6. Volume with Equation 10.

Method 5: Stand volume model (Equation 12).

The results of comparisons of different methods are presented in Table 3. The most accurate results are obtained when the estimated Weibull and stand height curve parameters are used (method 1). However, this is not possible in the application phase. When predicted parameters are used, the best alternative is method 3, but also method 2 is close to that. With method 4 the results are the most inaccurate. With methods 2 and 3, in which the parameter *b* was calculated using Equation 4, the predicted value was quite close to the observed value due to very high correlation between the mean diameter of the stand and the parameter *b* (Figure 2). When method 4 is used, this correlation is lost. The use of the stand volume model (method 5) leads to slightly better results than the use of the treewise models (methods 1-4).

Table 3. The accuracy of different methods in prediction of stand volume (n=145)

	Bias (%)	RMSE (%)	RMSE (m^3)
Method 1	0.6	1.4	1.2
Method 2	2.6	6.6	5.5
Method 3	2.1	6.1	5.2
Method 4	6.3	11.0	8.9
Method 5	0.9	4.9	4.2

The corresponding test results were calculated for the merchantable part of the stock. In these calculations Equation 11 was used to obtain merchantable volume treewise. The top diameter limit used was 7 cm. In the case of the merchantable part of the stock, the standwise volume model (Equation 12) could not be used. The results are presented in Table 4.

Table 4. The accuracy of different methods in prediction of merchantable stand volume (n=145)

	Bias (%)	RMSE (%)	RMSE (m^3)
Method 1	0.6	2.2	1.9
Method 2	3.4	7.9	6.6
Method 3	2.4	7.3	6.1
Method 4	8.1	13.4	10.6

The results show the same trend as in the comparison of stand total volume: method 1 was by far the most accurate, methods 2 and 3 were quite close to each other, and method 4 was the most inaccurate. The obtained biases and root mean square errors are higher than in the case of total stand volume. However, the error terms obtained with methods 2 and 3 are still clearly below 10%.

The accuracy of the different methods was further tested by calculating the error terms for 18 thinned plots which were not used in developing the models. The results are presented in Tables 5 and 6. According to the results, the accuracy of the different methods was even better in thinned plots. This may, however, be due to the small number of thinned plots, which decreases the reliability of these results. When unthinned plots were considered, slight underestimates (positive biases) were obtained. In the case of thinned plots, overestimates were obtained. Method 4, which was the most inaccurate in volume prediction of unthinned plots, was now the most accurate method. Methods 2, 3 and 5 were quite close to each other. The largest bias was obtained using the stand volume model. This shows that the flexibility of treewise models may be greater than that of a standwise model.

Table 5. The accuracy of different methods in prediction of stand volume. Thinned plots (n=18)

	Bias (%)	RMSE (%)	RMSE (m^3)
Method 1	0.3	0.7	0.9
Method 2	- 1.7	4.4	5.8
Method 3	- 2.0	4.8	6.3
Method 4	1.3	3.2	4.0
Method 5	- 2.3	4.3	5.6

Table 6. The accuracy of different methods in prediction of merchantable stand volume. Thinned plots (n=18)

	Bias (%)	RMSE (%)	RMSE (m^3)
Method 1	0.3	0.9	1.1
Method 2	- 2.0	4.5	5.5
Method 3	- 2.3	4.8	5.9
Method 4	1.3	3.0	3.6

Discussion

The purpose of this study was to develop a method for calculating stand volume characteristics of *Acacia mangium* stands based on treewise models utilising only a few measured stand variables. In the method, stand volume is predicted in three stages. Firstly, the theoretical diameter distribution is formed. This is done by predicting the parameters of the Weibull function, calculating the cumulative Weibull distribution and dividing it to theoretical trees. Secondly, parameters of the general height model are predicted separately for each stand and heights are calculated for trees obtained from the Weibull distribution. Finally, volumes of the trees are calculated using the treewise volume model with predicted tree diameters and heights. The sum of the tree volumes scaled to the stem number per hectare in diameter classes gives the stand volume per hectare. In addition to total stand volume, also merchantable stand volume or characteristics in a certain part of the stock can be calculated.

The advantage of the two-parameter approach of the Weibull distribution is achieved in the application phase when only one parameter needs to be predicted and the other can be calculated. In this study, the parameter *b* was more easily modelled than the parameter *c*. This has also been the case in some earlier studies (Saramäki 1992, Maltamo *et al.* 1995). Also the test criteria showed better fits when *b* was modelled.

The choice of the two-parameter approach of the Weibull distribution may cause some problems in applications where the stock of a stand is bigger than in this study. The starting point of the two-parameter approach is always zero. Consequently, in stands where very small trees are lacking, some extra trees may be generated by the model. However, their proportion of the stand volume is negligible. The use of the three-parameter approach of the Weibull distribution might help in these cases, but the maximum likelihood estimation and modelling of the parameters will then be more complicated (Maltamo *et al.* 1995).

It is possible to develop general height curves, because the development of the form of individual stand height curve for different tree species follows a species specific pattern over time (Prodan 1965). A general height curve can be used in stand inventories instead of individual stand height curves in order to minimise the amount of measurements needed. Furthermore, by using a general height curve the bias can be avoided, which may occur in individual stand height curves if the sample of heights is not representative. According to the models, the shape of the height-diameter relationship was dependent on the stage of development and the density of the stand.

It seems that with the general height curve it is possible to describe adequately also the structure of young stands that do not yet fully occupy the site. This is due to the fact that dominant height was the most effective variable in explaining the form of the stand height curves also in these stands. A small bias may, however, be introduced when the model is used in young stands, as stand density does not yet affect their development. This bias in young stands will be the greater, the more stand density deviates from the average in the data. In absolute terms, the bias in predicted tree heights will be small. As such stands constituted only a minor part of the data, the parameter estimates of the general model have probably not been seriously affected.

Thinning from below changes the density and mean diameter of the stand, but does not usually affect dominant height at all and the parameters of the stand height curves only a little (sample trees do not remain the same and the removed trees may have a different diameter-height relationship). Thus, a bias is automatically introduced in the model immediately after thinning, unless the removed trees are also known and used in the prediction. After thinning, the diameter-height relationship is strongly changed and the general model is no longer valid. It seems, however, that as the stand develops after thinning for two or three years, the model may be usable again, which can be seen in Figures 4 and 5.

Equations were also developed for the estimation of tree total and merchantable volumes. It seems that a simple model is able to describe the proportion of merchantable timber very accurately up to different top diameter limits. However, the model was fitted using observed volume up to top diameters of 5 and 10 cm, as pulpwood is the probable end-product of *A. mangium.*

The accuracy of the stand volume model was slighly better than that of the treewise models. The use of the stand volume model is restricted to calculation of total stand volume. The advantage of treewise models is achieved when a certain part of the stock is examined. Instead of total stand volume, the interest may also be in the diameter distribution of the stand, and models are now available for purposes of this kind.

Fitting of diameter distributions with the maximum likelihood method and modelling of the parameters was very accurate. This may be partly due to the fact that plantation forests are uniform in structure. The application of the method should be restricted to plantations. So far, stands of *A. mangium* have been established (perhaps exclusively) by planting.

The seed origin of the stands used in this study varied. Seed origin may affect the structure of the stand (cf. Beets & Kimberley 1993). This may have caused some extra variation in the models that could not be taken into account. On the other hand, Bufort and Burkhart (1987) found that the height-age relationship is affected by the seed origin only via dominant height at a given age and that stem taper is not affected by the seed origin in *Pinus taeda.* They concluded that a single volume yield model that does not take seed origin into account is sufficient. Thus, no major bias is expected when using the models presented here for *A. mangium.*

The model presented here can be used in conjunction with suitable growth models, such as those developed by Forss *et al.* (1996) for *A. mangium.* One way is to predict the development of different stand characteristics with whole stand growth models up to any future age and then predict the single tree characteristics and stand volume with the models presented in this paper. Another possibility is to predict the development of the stand with single tree growth models using the tree characteristics obtained from a stand inventory with the models presented here as input.

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