DOMINANT HEIGHT AND SITE INDEX MODELS FOR *Acacia mangium* Willd. PLANTATIONS

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ABSTRACT

Accurate estimate of site productivity (site quality) is essential for making sound forest management decisions. Site index, defined as dominant height of a stand at a base age, is often used to measure site quality. In this study, seven algebraic difference equations (ADE) based on the models proposed by Chapman-Richards, Lundqvist-Korf and McDill-Amateis were tested for fitting site index models for *Acacia mangium* Willd. plantations in South Sumatra, Indonesia. The models were fitted using re-measured, permanent plot data that involves non-overlapping growth intervals. The issues of serial correlation and heteroscedasticity in regression errors were tested, but not significant for any model. Numerical and graphical analyses were used to evaluate the performances and predictive abilities of the models. Results indicated that the models having an explicit asymptote parameter generally had greater accuracy and precision of parameter estimates and dominant height predictions, and could be applied for producing polymorphic site index curves. The selected model was the model derived from the Lundqvist-Korf function, which provided the best compromise between statistical and biological considerations and produced the most adequate site index curves. A base age of 6 years was proved to be best for prediction applications of the selected model. The model had a superior performance in terms of predictive ability and flexibility in use when compared to previously developed models for *A. mangium*.

Keywords: Site quality, dominant height, algebraic difference equation, polymorphic, *Acacia mangium*

I. INTRODUCTION

Accurate classification of site productivity (site quality) is essential for making sound forest management decisions. To do so, the variability of site quality over spatial and temporal scales of the managed forest estate must be quantified. The quality of a site can be defined as the wood production potential for a particular tree species or forest type (Clutter *et al.*, 1983). The most commonly used measure of site quality is site index, defined as dominant height of a stand at an index age. Dominant height, usually defined as average height of a specific number of the

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largest diameter or tallest trees for a given unit area, is regarded as one of the most useful measure of the site quality because it is little affected by variation in stand density or by most thinning regimes.

There are three general methods for constructing site index curves (Clutter *et al.*, 1983): (1) the guide curve method, (2) the parameter prediction method, and (3) the difference equation method. The guide curve method assumes proportionality which involves fitting an average curve through all dominant height-age data points. A set of anamorphic site index curves is then produced by making all curves proportional to their average or "guide" curve. Accordingly, the relative rates of dominant height growth are assumed to be constant across site index classes.

The parameter prediction method involves: (1) estimating a site index model for each modelling unit (e.g. stand, plot), (2) assigning a value of site index using each estimated model to the modelling unit, and (3) relating the parameters of the estimated models to site indices through regression procedures. The method can produce polymorphic site index models, which estimate the relative rates of dominant height growth varying over site index classes. Although the parameter prediction method has the advantage of great flexibility, it requires preliminary knowledge (*a priori* estimate) of site index or site index classes for individual modelling units before developing a site index model (Alder, 1980).

The difference equation method was introduced by Bailey and Clutter (1974) for developing the growth models for projecting the dominant height (H_1) measured at stand age A_1 into a future stand age A_2 (H_2). Thus growth models have been called the 'algebraic difference equation' (ADE) models for growth and yield projection (Borders *et al.*, 1984). To derive an ADE model based on a generic growth model (e.g., the Chapman-Richard function described by Pienaar and Turnbull, 1973), the method involves solving one parameter of the general model as a function of initial age (A_1), dominant height at initial age (H_1), and the other parameters; and substituting that solution into the model to express dominant height (H_2) at the future age (A_2) as a function of A_2, A_1, and H_1 (Ramírez-Maldonado *et al.*, 1988). Depending on which parameter of the generic growth model is constrained to be constant over stand ages (Clutter *et al.*, 1983, page 51), different ADE models may be obtained. In general, constraint in the asymptote parameter produces proportional (anamorphic) site index curves with different asymptotes. Constraint in the rate or shape parameter may produce polymorphic site index curves with a common asymptote.

Of the three methods, the ADE method is generally preferred as it combines both dominant height and site index predictions into a single model (Clutter *et al.*, 1983); no prior estimates of the site index need to be determined for each modelling unit; and the choice of base age does not affect significantly the shape of site index curves. Other desirable properties of this method are that it can use effectively data measured over a relatively short period of time (Elving and Kiviste, 1997), and that height predictions follow the height growth pattern with no illogical, declining heights for any prediction period (Rose *et al*., 2003).

Studies have been made for *Acacia mangium* dominant height (site index) models in Indonesia. However, these models were constructed using different methods and based on limited data from a small number of plots over narrow age range so the usefulness of these models is limited. For example, Harbagung (1991) based his work only on twelve experimental plots using the parameter prediction method; Forss *et al.* (1996) based their work on 24 semi-permanent plots from predominantly young stands using the difference equation method; and Nirsatmanto *et al*. (2003) based their work on 58 permanent plots using a guide curve method. In this study we develop a compatible dominant height and site index model for *A. mangium* plantations that provide a major improvement over the previous models. The model was derived from the data of 197 permanent plots using the ADE method.

II. MATERIALS AND METHODS

A. Data Description

Data came from 197 permanent plots established in unthinned *A. mangium* plantations located in South Sumatra, Indonesia. The plots were subjectively selected to represent the range of stand age, density (spacing) and site quality of *A. mangium* plantations in the region. All plots were established with the same size (0.1 ha), but the stands sampled varied in planting spacing (i.e. 3x2, 3x3, 3x4 and 2x4 m). They were established between 1993 and 1996 and the first measurements were taken 2-4 years after planting. Most plots were measured at a 1-year time interval until 8-11 years after planting; but there were a few occasions that the re-measurements were conducted at 2-year time intervals. A total of 1172 measurements were available for this study.

The data were divided into fitting and validation data sets. One hundred and forty-eight plots established between 1993 and 1995 were used for model fitting, while 49 plots established in 1996 were used for model validation. There were a total of 866 measurements available for fitting and 306 for validation. Summary of statistics description regarding dominant height data were calculated for both fitting and validation data (Table 1).

In this study, dominant height of the stand is defined as the average height of the 100 largest-diameter trees per ha. Because diameter over bark at 1.3 m above the ground (d) was measured for all trees, but total height (h) was only measured for a sample of trees in the plot, a height-diameter relationship (model) was estimated by plots using the trees having both d and h measurements. The model was applied to predict h for trees having no h measurements. Mean height of the 10 largest-diameter trees in each plot was then calculated to estimate dominant height.

Table 1. Summary of the statistics description for dominant height growth data for the model fitting and validation data sets.

Age (years)	Fitting data					Validation data				
	n	Mean (m)	SD (m)	Min (m)	Max (m)	*n*	Mean (m)	SD (m)	Min (m)	Max (m)
2	20	7.5	1.9	5.0	10.7	12	7.0	1.7	5.0	9.5
3	88	10.0	2.3	3.6	14.0	32	9.9	2.2	5.5	14.0
4	132	13.1	2.7	5.1	18.7	49	12.7	2.3	8.0	17.3
5	133	15.8	2.7	9.0	21.6	49	14.9	2.4	10.1	20.0
6	121	17.6	2.6	11.6	23.2	49	17.1	2.4	13.2	22.8
7	137	19.9	2.7	14.0	25.4	47	19.0	2.2	15.2	23.9
8	125	21.4	2.7	15.2	28.6	45	20.7	2.2	16.0	24.8
9	76	23.1	2.5	16.2	28.0	17	21.7	1.8	18.2	25.5
10	30	23.9	2.3	18.2	26.9	6	22.8	1.8	21.3	26.3
11	4	23.5	3.1	20.8	28.0					
Total	866					306				

Notes: SD is standard deviation; Min is minimum height; Max is maximum height; n is number of observations

B. Alternative Functional Forms

Many mathematical functional forms have been proposed in the literature for modelling the dominant height-age relationship and developing site index models. Goelz and Burk (1992) discussed the desirable characteristics of a site index model, which include logical behaviour (e.g. predicted dominant height should be equal to site index estimate at the base age), sigmoidal growth pattern (curve), polymorphism, and path invariance for prediction. In this study, three nonlinear generic growth models that meet these criteria were selected as base models for relating dominant height to stand age. The selected base models were the Chapman-Richards function (Richards, 1959; Chapman, 1961), the Lundqvist-Korf function (cited in Amaro *et al.*, 1998), and the McDill-Amateis function (McDill and Amateis, 1992).

The Chapman-Richards (CR) function was first used for modelling forest growth by Pienaar and Turnbull (1973) and has proven to be very flexible in modelling the growth for a range of stand characteristics, including dominant height (e.g. Amaro *et al.*, 1998; Chen *et al.*, 1998). The CR function is usually expressed in the integrated form:

$$H = b_0\left(1 - \exp(-b_1 A)\right)^{b_2} \quad \text{.......} \quad (1)$$

where H is dominant height (m), A is stand age (years), b_0, b_1 and b_2 are the asymptote, rate and shape parameter to be estimated, respectively.

The Lundqvist-Korf (LK) function can be viewed as a generalization of the Schumacher function (Schumacher, 1939), and has been used to model dominant height-age relationship in many studies of forest growth (e.g. Elving and Kiviste, 1997, Anta and Diéguez-Aranda, 2005). The integrated form of the LK function is:

$$H = b_0 \exp\left(\frac{-b_1}{A^{b_2}}\right) \quad (2)$$

where all variables in Eq. 2 were defined as those in Eq. 1.

The McDill-Amateis (MA) function (McDill and Amateis, 1992) was derived using a dimensional analysis method (Amateis and McDill, 1989), and has been used by several researchers for developing site index models (e.g. Fontes *et al*., 2003; Palahí *et al*., 2004). The MA function has no integrated form, and the ADE form suggested by McDill and Amateis (1992) was:

$$H_2 = \frac{b_0}{1 - \left(1 - \left(\frac{b_0}{H_1}\right)\right)\left(\frac{A_1}{A_2}\right)^{b_1}} \quad (3)$$

where the subscripts 1 and 2 refer to the initial age (years) and prediction age (years), respectively, b_0 is the asymptote parameter, and b_1 is the shape parameter.

In this study, the ADE forms of the CR and LK functions when the asymptote, rate or shape parameter was constrained, along with the ADE form of the MA function were selected to be the candidate models for testing to determine the best model for developing the dominant height and site index models for *A. mangium* plantations (Table 2).

Table 2. The algebraic difference-equations tested for modelling dominant height and site index.

Model	Generic growth function	Algebraic difference-equation model
CR-1	Chapman-Richards solved for b_0	$H_2 = H_1\left(\frac{1-\exp(-b_1 A_2)}{1-\exp(-b_1 A_1)}\right)^{b_2}$
CR-2	Chapman-Richards solved for b_1	$H_2 = b_0\left(1-\left(1-\left(\frac{H_1}{b_0}\right)^{1/b_2}\right)^{A_2/A_1}\right)^{b_2}$
CR-3	Chapman-Richards solved for b_2	$H_2 = b_0\left(\frac{H_1}{b_0}\right)^{\frac{\mathrm{h}\,(1-\exp(-b_1 A_2))}{\mathrm{h}\,(1-\exp(-b_1 A_1))}}$
LK-1	Lundqvist-Korf solved for b_0	$H_2 = H_1 \exp\left(b_1\left(\left(\frac{1}{A_1{}^{b_2}}\right)-\left(\frac{1}{A_2{}^{b_2}}\right)\right)\right)$
LK-2	Lundqvist-Korf solved for b_1	$H_2 = b_0\left(\frac{H_1}{b_0}\right)^{(A_1/A_2)^{b_2}}$
LK-3	Lundqvist-Korf solved for b_2	$H_2 = b_0 \exp\left(-b_1 A_2{}^{\mathrm{h}\left(\frac{\mathrm{h}\,(H_1/\,b_0)}{-b_1}\right)\Big/\mathrm{h}\ A_1}\right)$
MA	McDill-Amateis	$H_2 = \frac{b_0}{1+\left(\frac{b_0}{H_1}-1\right)\left(\frac{A_1}{A_2}\right)^{b_1}}$

Notes: A_1 is initial age (years); A_2 is prediction age (years); H_1 is dominant height at age A_1 (m); H_2 is dominant height predicted at age A_2 (m); and b_0, b_1 and b_2 are model parameters to be estimated

C. Model Parameterization

In general, the candidate models selected for testing (Table 2) can be expressed as the following statistical model:

$$Y_i = f(X_i, \beta) + \varepsilon_i \quad \text{.......} \quad (4)$$

where Y_i is a vector of observations of the dependent variable (H_2), X_i is a matrix of observations of the explanatory variables (H_1, A_1, A_2), b is a vector of parameters (b_0, b_1, b_2) to be estimated, e_i is a vector of random errors, i = 1, 2, ...n, and n is the number of observations.

The underlying assumption for such a statistical model is that the random errors e_i are independent and identically distributed (i.i.d) variables, following the normal distribution with zero mean and a constant variance σ_ε^2. Because repeated measurements from permanent plots are used for estimating the models, these assumptions may not be met, and the random errors associated with the estimated models may be autocorrelated and heteroscedastic (West *et al*., 1984). Under this situation, the standard errors of parameter estimates obtained using linear or nonlinear ordinary least squares method are biased and inconsistent thereby invalidating standard statistical hypothesis testing and interval estimation procedures.

To avoid using an estimated model with undesired statistical properties the residual analyses were performed for identifying any violation of the underlying statistical assumptions (e.g. heteroscedastic errors). In addition, statistical tests, such as the Durbin-Watson test (Durbin and Watson, 1971) were applied to test if the autocorrelation of the errors was statistically significant. All analyses were done using the MODEL procedure of the SAS/ETS program (SAS Institute Inc, 2005).

Residual plots from preliminary fitting of the seven candidate models using the dominant height growth data from all non-overlapping intervals of measurements showed no obvious indication of violating the underlying statistical assumptions, and the Durbin-Watson test statistics estimated for the seven candidate models ranged from 1.796 to 1.982, which were generally not statistically significant at 5% probability level compared to the critical value provided in Savin and White (1977). This implied that the serial correlation of errors was not significant for any model.

D. Model Evaluation

Performance of the estimated models was evaluated quantitatively and qualitatively, and both empirical and biological issues were addressed. A three-step procedure was used to select the most appropriate model. Step 1 was based on the fit statistics, such as asymptotic *t*-statistics, root mean squared error (*RMSE*), adjusted coefficient of determination (R^2_{adj}), and residual analysis. Step 2 was based on validation statistics using the data set that is independent of model estimation process (i.e. the reserved or validation data). This step is important since the quality of fit does not necessarily reflect the quality of the prediction (Huang, 1997; Myers, 2000).

Four validation statistics based on the differences between observed and predicted values from the estimated models recommended by Vanclay and Skovsgaard (1997) and Huang *et al*. (2003) were used in this study: (1) mean residual (*MRES*), which measures the systematic deviation (bias) of the predictions; (2) absolute mean residual (*AMRES*), similar to *MRES* but ignoring the sign of the errors; (3) root mean squared error (*RMSE*), which measures the accuracy of the predictions; and (4) the adjusted model efficiency (MEF_{adj}), which is an index of model performance on a relative scale. In addition, Akaike's information criterion

(*AIC*), which is an index for selecting the best model on the basis of minimising the Kullback-Liebler distance (Burnham and Anderson, 1998), was also evaluated. These validation statistics were estimated as follows:

$$MRES = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \quad (5)$$

$$AMRES = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i|}{n} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p}} \quad (7)$$

$$MEF_{adj} = 1 - \frac{(n-1)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (8)$$

$$AIC = n \ln \hat{\sigma}^2 + 2(p+1) \quad (9)$$

where y_i, $\hat{y}_i$, and $\bar{y}$ are the observed, predicted and average values of dependent variable (dominant height), respectively; *n* is the total number of observations used to evaluate the models; *p* is the number of model parameters; and $\hat{\sigma}^2$ is the error variance of the fitted model estimated as:

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n} \quad (10)$$

Step 3 involved assessment of whether the models were consistent and made biological sense. This was done by taking into account all information available on *A. mangium* growth patterns. Some biological aspects considered were: (1) values and signs of the coefficients or parameters in the models, (2) quality of extrapolations outside the range of site indices as well as outside the age range of the data, and (3) height curve development at younger and older ages. The examination based on the appearance of the fitted curves is important in selecting the most appropriate model since curve profiles may differ considerably, even though goodness-of-fit statistics are similar (Huang, 1997).

With all evaluations discussed above, the most adequate model for describing dominant height growth of *A. mangium* stands was then determined, and the final model was then estimated using all available data, i.e. pooled fitting and validation data (Myers, 2000).

E. Selection of a Base Age

The use of site index model requires setting a base age for site index estimation (Clutter *et al*., 1983). The base age is referred to as reference or index age. Different base ages have been used in previous site index modelling studies for *A. mangium* plantations. For example, a base age of 5 years was used by Forss *et al*. (1996), of 8 years used by Nirsatmanto *et al*. (2003), and of 12 years used by Harbagung (1991). However, no discussions were given in these previous studies on why these base ages were selected. According to Goelz and Burk (1992), the base age should be: (1) less than or equal to the shortest rotation for a typical management regime, (2) close to the actual rotation age, and (3) able to give reliable predictions of dominant height from the site index models for any stand ages other than the base age. In Indonesia and other tropical countries, the typical rotation age used for managing *A. mangium* plantations, particularly for pulpwood production, varies between 6 and 8 years (Lemmens *et al*., 1995).

To select the best base age for application of the final dominant height and site index model, different base ages covering the range of rotation ages as well as age ranges of the data were examined, and the best base age was then selected based on the validation statistics described earlier.

III. RESULTS AND DISCUSSION

All the candidate models were estimated using the nonlinear ordinary least squares method; and the parameter estimates, associated standard errors, and other fit statistics are summarised in Table 3. All candidate models resulted in similar fit statistics, which indicated that all fitted the available dominant height data relatively well. All parameter estimates were found to be highly significant at the 1% probability level and the models explained 91% or more of the total variation in the measured dominant heights.

Each of the models was applied for predicting dominant heights for every data points included in the validation data, and the validation statistics were estimated (Table 4). Mean prediction errors of the candidate models were generally small (i.e. the values of $MRES$ < 0.2 m, $AMRES$ < 1.0 m, and $RMSE$ < 1.3 m). The resultant values of the adjusted model efficiency were 90% or higher for all models. Comparing the resultant values of AIC, the models CR-1, LK-1, and LK-3 were relatively higher, indicating these three candidate models were poorer for predicting dominant heights.

Overall, models CR-2 and CR-3 derived from the Chapman-Richards function solved for parameters b_1 and b_2, respectively; model LK-2 derived from the Lundqvist-Korf function solved for parameter b_1, and model MA proposed by McDill and Amateis (1992), produced the preferable results against the selected criteria discussed earlier. Model CR-1 derived from the Chapman-Richards function when solved for parameter b_0 and model LK-1 derived from the Lundqvist-Korf function also solved for parameters b_0 performed less preferable. Model LK-3 derived from the Lundqvist-Korf function solved for parameter b_2 performed the worst. Therefore, this candidate was eliminated from further examination.

Table 3. Parameter estimates, standard errors (*SE*) and fit statistics of the seven candidate dominant height and site index models.

Model	Parameter	Estimate	*SE*	*t*	$P < \mid t \mid$	*RMSE*	R^2_{adj}
CR-1	b_1	0.168	0.018	9.6	0.0001	1.262	0.918
	b_2	1.09	0.059	18.3	0.0001		
CR-2	b_0	28.9	0.660	43.7	0.0001	1.169	0.929
	b_2	1.26	0.058	21.7	0.0001		
CR-3	b_0	31.8	1.020	31.2	0.0001	1.131	0.934
	b_1	0.153	0.013	11.8	0.0001		
LK-1	b_1	3.09	0.119	25.9	0.0001	1.267	0.917
	b_2	0.45	0.053	8.5	0.0001		
LK-2	b_0	48.42	3.761	12.9	0.0001	1.161	0.930
	b_2	0.64	0.046	13.8	0.0001		
LK-3	b_0	38.2	2.010	19.1	0.0001	1.305	0.912
	b_1	2.97	0.061	49.4	0.0001		
MA	b_0	34.5	1.280	26.9	0.0001	1.165	0.930
	b_1	1.36	0.052	26.2	0.0001		

Table 4. Validation statistics of the seven candidate dominant height and site index models.

Model	*MRES* (m)	*AMRES* (m)	*RMSE* (m)	MEF_{adj}	*AIC*
CR-1	0.134	0.878	1.203	0.911	98.87
CR-2	-0.053	0.823	1.122	0.922	63.16
CR-3	-0.138	0.793	1.060	0.931	33.78
LK-1	0.134	0.880	1.202	0.911	101.72
LK-2	-0.046	0.827	1.123	0.923	64.85
LK-3	0.154	0.928	1.288	0.897	135.11
MA	-0.048	0.824	1.120	0.923	63.25

To further evaluate the remaining candidate models, dominant height predictions (growth curves) obtained from each candidate were examined. The predictions of dominant height were made for the site index classes of 11, 14, 17, 20, and 23 m respectively, covering the site index range observed in the data. In deriving these predictions, the H_1 and A_1 in each candidate model were set to be the site index and base age (arbitrarily set as 6 years) (Figures 1-a-f).

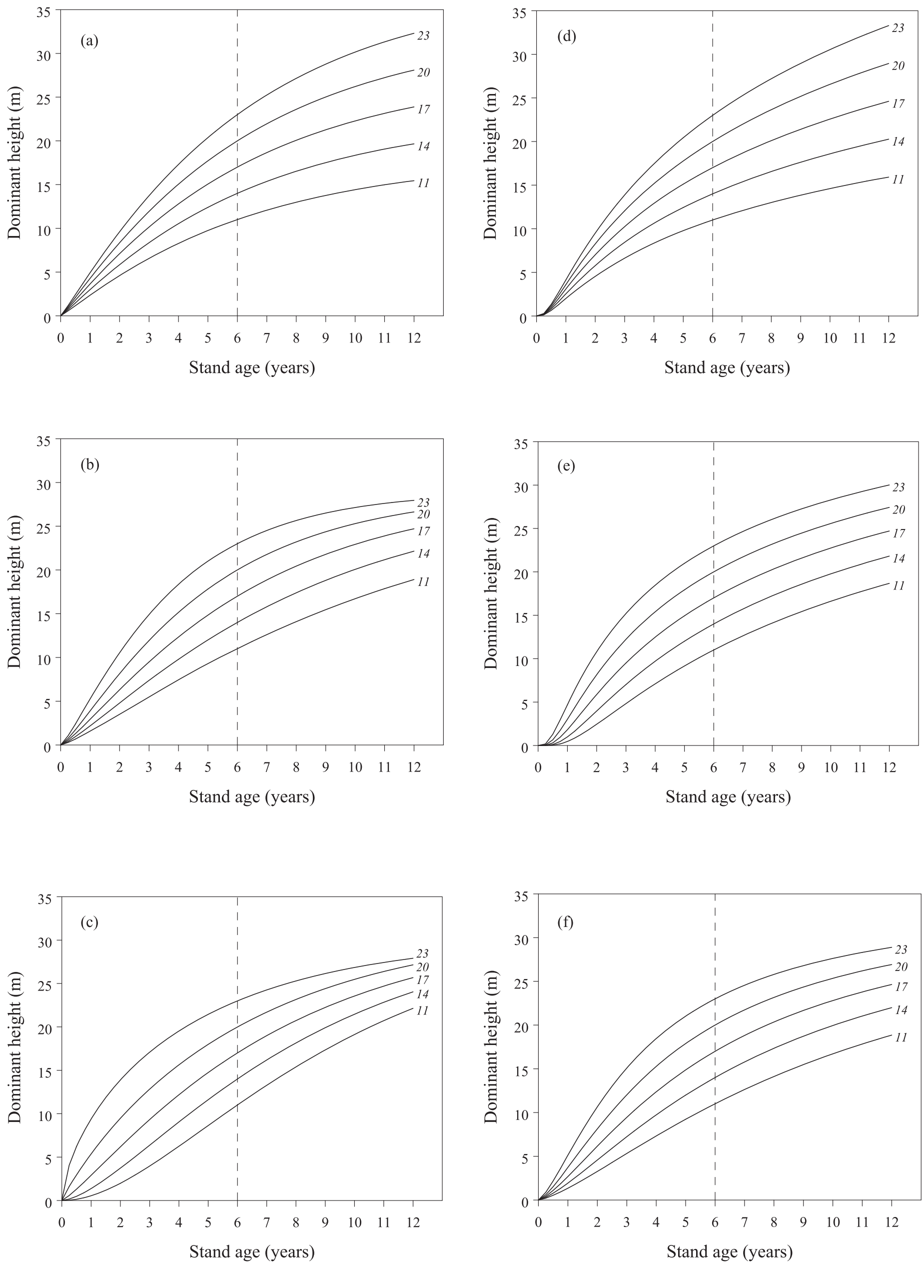

Figure 1. Dominant height growth curves for site indices 11, 14, 17, 20, and 23 m at a base age of 6 years for models CR-1 (a), CR-2 (b), CR-3 (c), LK-1 (d), LK-2 (e), and MA (f).

Model CR-1 derived from the Chapman-Richards function (Figure 1-a) and model LK-1 developed from the Lundqvist-Korf function (Figure 1-d) both solved for the asymptote parameter b_0 were discarded based on the visual inspection of the fitted curves. Although the models derived without explicit estimation of the asymptote may have the advantage of easy parameterisation, these models produced unrealistically high dominant height predictions at later stages of stand development. Extrapolation outside the ranges of the data used in model estimation would result in unrealistic prediction. In addition, both models CR-1 and LK-1 produced anamorphic growth curves for different site index classes. As indicated by Goelz and Burk (1992) and Parresol and Vissage (1998), those anamorphic site index curves may not be appropriate, because the rate parameter (b_1) has been found generally to be dependent on site quality.

All four remaining models (i.e. models CR-2, CR-3, LK-2, and MA in Table 2) have the asymptote parameter b_0 and can produce polymorphic site index curves. Model CR-2 (Figure 1-b) appeared to be lack of flexibility for predicting polymorphism for dominant height growth at later ages. Additionally, this model had a very low asymptote parameter estimate (b_0 = 28.9 in Table 3), but other studies reported that dominant height of *A. mangium* plantations could exceed 30 m (e.g. Gunn and Midgley, 1991; Pinyopusarerk *et al.*, 1993). Furthermore, dominant height curves derived from model CR-2 did not perform well when extrapolating beyond the age and site index ranges of the data.

Model CR-3 (Figure 1-c) did not reflect the dominant height growth pattern observed in the data. This model predicted a very rapid increase in height at relatively young ages, particularly on the higher site index classes and considerably overestimated dominant height at young ages. Although model CR-3 had the best validation statistics (Table 4), it gave illogical predictions at young ages. In addition, the model performed poorly at later ages.

The poor performance of both the Chapman-Richards models (CR-2 and CR-3) was unexpected, because many authors found that this functional form performed well for other species in modelling dominant height (e.g. Amaro *et al.*, 1998; Diéguez-Aranda *et al.*, 2005). However, our result showed that it was not appropriate for modelling *A. mangium* in this study. Therefore, both models CR-2 and CR-3 were not considered for further examination.

Model LK-2 derived from the Lundqvist-Korf function solved for parameter b_1 and model MA proposed by McDill and Amateis (1992) had very similar goodness-of-fit and validation statistics (Tables 3 and 4). Although dominant height curves generated from model MA (Figure 1-f) appeared to be reasonable, the model produced illogical predictions beyond the age range of the available data, especially at the high site index classes. This result was similar to those obtained for models CR-2 and CR-3 at older ages. Model MA was therefore not preferred.

Model LK-2 derived from the Lundqvist-Korf function solved by elimination of parameter b_1 (Figure 1-e) performed best compared to other models and predictions from this model closely mimicked the growth pattern of *A. mangium* plantations observed in the data. This model predicted realistic development at young ages and produced sensible site index curves when extrapolating outside the ranges of data.

In selecting the best dominant height and site index model, a compromise between desirable biological and statistical performance was considered, rather than a pure statistical inference. Inspection of the dominant height growth curves derived from different candidate models revealed that, depending on which parameter of a generic growth function was constrained, the shapes of growth curve could be different, even though fit and validation statistics were similar. Comparing the fit and validation statistics only are not sufficient for judging the 'good' or 'bad' models (Huang, 1997), then the characteristics of predictions must be compared with the reality of forest growth. Based on these considerations, model LK-2 was selected to be the most appropriate for modelling the dominant height and site index of *A. mangium* plantations.

The selected model LK-2 can be used to project the dominant height measured at a given age into any future ages, and to derive the site index estimate from a measured dominant height-age pair, as well as to generate the dominant height growth curves for any specified values of site index. For these applications, model LK-2 can be represented as:

1. to project a measured dominant height-age pair (H_1, A_1) to any future age (A_2):

$$\hat{H}_2 = 51.7\left(\frac{H_1}{51.7}\right)^{(A_1/A_2)^{0.59}} \qquad \text{...(11)}$$

2. to estimate site index (S) with the base age A_b based on a measured dominant height-age pair (H, A), substitute S for H_2, A_b for A_2; and consecutively H and A for H_1 and A_1:

$$\hat{S} = 51.7\left(\frac{H}{51.7}\right)^{(A/A_b)^{0.59}} \qquad \text{...(12)}$$

3. to generate dominant height growth curves for a given site index (S) and base age A_b, simply substitute S for H_1 and A_b for A_1, and H and A for H_2 and A_2:

$$\hat{H} = 51.7\left(\frac{S}{51.7}\right)^{(A_b/A)^{0.59}} \qquad \text{...(13)}$$

Before the developed model LK-2 can be applied for prediction applications, the base age A_b must be specified. As discussed earlier, the base age should be selected closely to the rotation age, and reliably for generating dominant height growth curves. In this study, we initially examined different base ages covering age ranges of the data, and selected the base age that had the smallest errors of dominant height predictions, which resulted in selection of a base age of 6 years (Figure 2). Selection of a younger base age may be useful for decision-making at early-age silvicultural treatments (Diéguez-Aranda *et al*., 2005). However, based on the results of our study, a base age younger than 4 years will result in unreliable estimates of site index due to high variability of height growth at early ages. Huang (1997) indicated that early height growth of trees might be erratic and often determined by factors other than site quality, such as initial stocking level, planting stock quality, site preparation methods and planting technique. Although previous site index models for *A. mangium* stands used various base ages (Harbagung, 1991; Forss *et al*., 1996; Nirsatmanto *et al*., 2003), we selected the base age of 6 years for obtaining reliable predictions of dominant height and site index estimates.

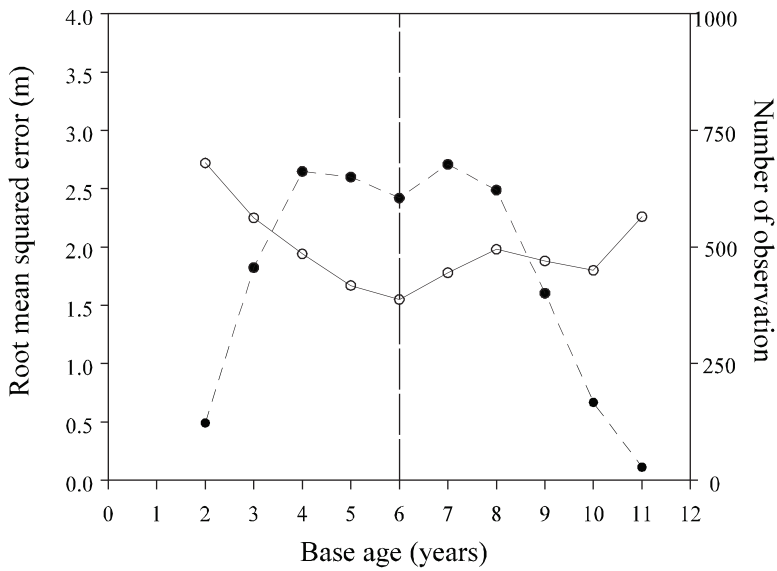

Figure 2. Root mean squared errors in site index predictions for different base ages using model LK-2 (*solid line*: root mean squared error, *dashed line*: number of observations).

In Figure 3, site index curves derived from model LK-2 are compared with previously developed site index curves. The anamorphic site index curves produced from the model developed by Forss *et al*. (1996) showed that the dominant height development of *A. mangium* plantations represented by the data available for this study was inaccurately described. More specifically, this model over-predicted dominant height at older ages for high site index values, but under-predicted at younger ages. The site index curves derived from the models developed by Harbagung (1991) and Nirsatmanto *et al*. (2003) under-predicted dominant heights for high site index values at younger ages, but over-predicted at older ages. The model LK-2 developed in this study followed the observed dominant height development generally well for the entire age range of the available data. It appears to provide a major improvement over the previous models for site classification and dominant height prediction for *A. mangium* stands in Indonesia.

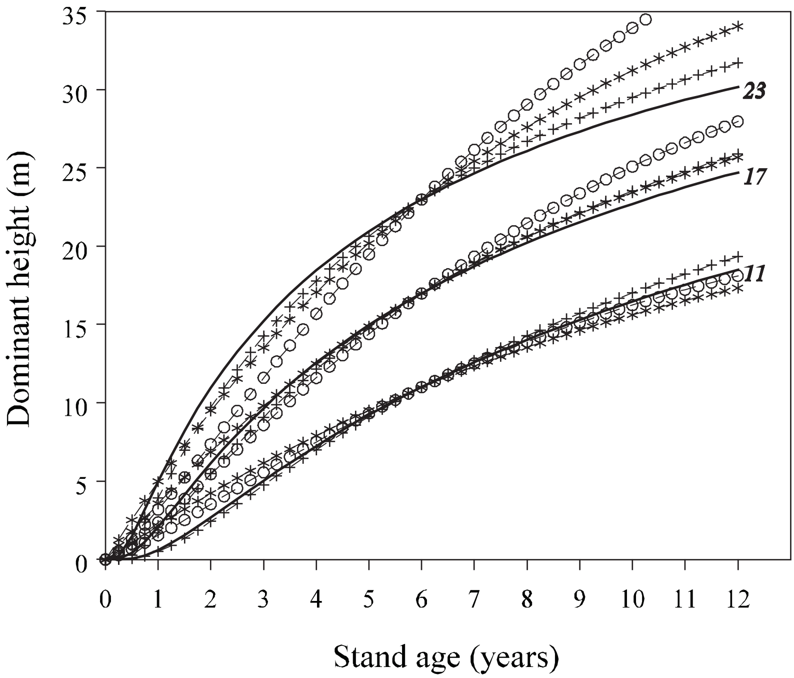

Figure 3. Comparison of dominant height growth curves for site indices 11, 17, and 23 m at a base age of 6 years developed in this *study* (using model LK-2) and dominant height models developed previously (*solid line*: model LK-2, *plus*: Harbagung's model, *circle*: Forss *et al.*'s model, *star*: Nirsatmanto *et al.*'s model).

IV. CONCLUSION

The algebraic difference equation method was used in this study for modelling dominant height and site index for *A. mangium* plantations. Seven candidate models were analysed and fitted to the permanent sample plot data from South Sumatra. All models present no strong serial correlation or heteroscedasticity.

The majority of the candidate models gave similar fit and validation statistics, so graphical analyses of the models and biological consideration were then important in selecting the most appropriate model. Based on the fit and validation statistics as well as graphical analyses, Model LK-2 derived from the Lundqvist-Korf function solved by eliminating parameter b_1 was selected for predicting dominant height and estimating site index, since it provided the best overall representation both statistically and biologically. The model produced polymorphic dominant height curves with the rate of dominant height growth varying between sites. The resulting model combines both dominant height and site index prediction into a single model.

A base age of 6 years was selected for site index estimation based on minimising the root mean squared error in site index predictions. A comparison of Model LK-2 with previous site index models for *A. mangium* plantations showed that this model was superior in terms of predictive ability and flexibility of use.

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