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MODELLING TREE DIAMETER GROWTH OF PLANTATION GROWN *DRYOBALANOPS SUMATRENSIS*

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AHMAD ZUHAIDI, Y. 2006. Modelling tree diameter growth of plantation grown *Dryobalanops sumatrensis*. This paper examines the diameter growth of planted *Dryobalanops sumatrensis* based on the results of measurements for all trees with diameter ≥ 10 cm collected between 1997 and 2000. The study was carried out at Bukit Lagong Forest Reserve, Selangor, Peninsular Malaysia. Least square method using transformed and weighted models was developed to relate periodic annual diameter increment to diameter, competition indices and environmental factors as independent variables. The results indicated that transformed model relating periodic annual diameter increment to diameter, competition indices (basal area and over-topping basal area) and environmental variables (elevation and slope) explained a significant proportion of the variation in the periodic annual diameter increment at 36.7% ($p < 0.05$). Overall results of the modelling were negatively biased and underestimated the predicted periodic annual diameter increments of the species.

Keywords: Periodic annual diameter increment, competition indices, environmental variables

AHMAD ZUHAIDI, Y. 2006. Unjuran pertumbuhan diameter pokok *Dryobalanops sumatrensis* yang ditanam di ladang. Kajian ini meneliti kadar pertumbuhan diameter dirian *Dryobalanops sumatrensis* berdasarkan ukuran diameter yang dibuat dari tahun 1997 sehingga tahun 2000 bagi semua pokok yang bersaiz ≥ 10 cm. Kajian unjuran ini dijalankan di dalam kawasan Hutan Simpan Bukit Lagong, Selangor, Semenanjung Malaysia. Kaedah ganda dua terkecil menggunakan model yang terjelma dan berwajaran telah dibina dengan menghubungkaitkan pertambahan diameter tahunan berkala dengan diameter, indeks persaingan dan faktor persekitaran. Keputusan analisis menunjukkan bahawa kaedah model terjelma yang menghubungi diameter, indeks persaingan (luas pangkal, luas atas pangkal pokok) dan faktor persekitaran (kedudukan pokok, kecerunan) menerangkan dengan signifikan variasi pertambahan diameter tahunan berkala sebanyak 36.7 % ($p < 0.05$). Keputusan keseluruhan unjuran menunjukkan pincang negatif dan yang bawah anggaran terhadap pertambahan diameter tahunan berkala yang diramal bagi spesies ini.

INTRODUCTION

Growth and yield models provide a quantitative description of forest stand development and enable predictions of growth and yields in forest management (Vanclay 1994). In recent years, modelling of growth and yield in natural and planted forests within the tropics have been widely developed. Despite the significant progress, there has been relatively little research to describe the growth of planted species in perhumid tropical rainforests particularly the tropical plantation forests of *Dryobalanops sumatrensis* (Dipterocarpaceae and formerly known *D. aromatica*) species.

Modelled prediction on the growth of *D. sumatrensis* in Peninsular Malaysia is still lacking, and the present study was conducted to provide decision-support for yield regulation. It has been shown that periodic annual diameter growth differed between plots of *D. sumatrensis* and the differences were dependent on stand characteristics, e.g. stand density (Ahmad Zuhaidi *et al.* 2003, 2004). Thus, in this study a model for diameter growth of the species was developed using the results of measurements for all trees with diameters ≥ 10 cm collected between 1997 and 2000. The growth model will be useful in forest management of this species and it will help to identify gaps in our knowledge underlying the growth of planted tropical forests species.

MATERIALS AND METHODS

The form of the growth model was based on the ecological concept of competition for resources between trees. Growth of trees was expressed as the periodic annual diameter increment, a function of diameter, between-tree competition and environmental variables affecting growth. Competition index refers to classification of competition indices as described in Vanclay (1994) and Phillips and van Gardingen (2001a). The classified category was the area potentially available to each tree, calculated by sharing the total plot area among the trees according to their size. Competition indices included absolute variables such as stand density and basal area (Ong & Kleine 1995), and competition environment for each tree in the plot, over-topping basal area, diameter independent competition index and over-topping shade index (Phillips & van Gardingen 2001b). Topographic features and environmental variables used in the growth model included site-specific factors (e.g. elevation, stand density and slope) that might influence growth of individual trees significant in determining the proportion of variation in diameter increment.

Dryobalanops sumatrensis is naturally distributed in Sumatra and Peninsular Malaysia. In Peninsular Malaysia, the forests are confined to two large blocks in the east coast (south of Terengganu and east of Johore) and one in a small pocket in the west coast, namely, Kanching Forest Reserve (Symington 1974). The species was also planted in Bukit Lagong Forest Reserve.

Study area

Bukit Lagong Forest Reserve is situated in Selangor in the western part of Peninsular Malaysia at a latitude and longitude of 3° 14' N and 101° 38' E respectively. The area has a humid climate with average daily temperatures ranging from 27 to 32 °C. The study sites are located at an elevation of 90 to 130 m asl on the lower slopes of the Lagong range. Records of the stand, plot establishment, source and method of collecting data on dbh and calculation of periodic annual diameter are described in Ahmad Zuhaidi *et al.* (2003).

The main component of the data used in this study was dbh for trees ≥ 10 cm. Six experimental plots were set up, varying in sizes from 0.21 to 0.96 ha. Periodic annual diameters of individual trees were calculated as an average of all annual dbh increments over the growth period between 1997 and 2000. Independent variables included stand and individual tree attributes. Competition indices were expressed as basal area, over-topping basal area, stand density, diameter independent competition and over-topping shade index. The environmental variables included slope, stand density and elevation of trees above sea level relative to a permanent benchmark in field 11, Bukit Lagong Forest Reserve, within the Forest Research Institute of Malaysia (FRIM).

Tree position

Positions of trees with dbh ≥ 10 cm were recorded. The distance of each tree was recorded in relation to the south-west corner of each plot and corrected for slope. The position of each tree was measured by holding one end of the tape at the middle portion of the trunk (usually at breast height) while the other end of the tape towards the direction aligned with the horizontal (x-coordinates) and vertical (y-coordinates) edges of the plot.

Tree elevation

Tree elevation was recorded for all individuals with dbh ≥ 10 cm based on a series of 10 × 10 m subplots. The elevation of each tree was recorded from the average elevation of the subplot measured using a levelling telescope, model TRACON S-25, Ushikata. The elevation of each subplot was recorded starting from a permanent reference point in FRIM (benchmark at 75.61 m asl). Using a pair of poles (3 m) and the levelling telescope both back and forward elevations were recorded from the permanent reference point to the first point on the plot. The same procedure was repeated until the closing point of the plot. The elevation of each tree within the subplot was the calculated following Ary *et al.* (1994).

Slope

The slope of each tree location was recorded at the steepest direction measured in the subplot (Alder & Synnott 1992) using an optical clinometer (model PM-5/400 PC, Suunto Company, Helsinki, Finland). Readings were taken in the north-south direction at every 10 m along the subplot centerlines. The slope of each tree in the subplot was calculated following Ary *et al.* (1994).

Observed periodic annual diameter increment

The periodic annual diameter increment (P_{obs}) was calculated as:

$$P_{obs} = [(d_{t+k} - d_t) / k] \times t \quad (1)$$

where

P_{obs} = observed periodic annual diameter increment (cm year^{-1})
d_{t+k} = diameter at the end of growth period (cm)
d_t = diameter at the beginning of growth period (cm)
k = length of growth period (days)
t = 365 days

The periodic annual diameter increment between 1997 and 2000 was expressed as an average of all annual increments over the growth period.

Stand density

Stand density was calculated using the formula as in Equation 2 (Phillip 1994) and expressed as per hectare values:

$$N = \frac{n}{A} \quad (2)$$

where

N = number of trees ha^{-1}
n = number of trees in the plot
A = area of the plot (ha)

Basal area

The basal area per tree was obtained using Equation 3 (Loetsch *et al.* 1973):

$$g = \frac{d^2\pi}{40\,000} \quad (3)$$

where

g = basal area per tree (m^2)
d = diameter at breast height (cm)

The basal area per ha was obtained by the sum of individual basal area corrected for the size of each individual plot (Equation 4):

$$G = \left(\frac{\Sigma g}{A}\right) \quad (4)$$

where

G = basal area (m^2 ha^{-1})
A = area of the plot (ha)

Over-topping basal area

Over-topping basal area is defined as the basal area of all trees with diameter greater than those of individual trees to be modelled (Vanclay 1991). The over-topping basal areas were calculated using SAS / STAT 1989 on the 10 × 10-m plot basis.

Diameter independent competition index and over-topping shade index

Competition indices were calculated using the SYMFOR modelling framework (Phillips & van Gardingen 2001a) with the tree identification, x and y positions of the trees, dbh, species group and utility group as base information. The over-topping shade index and diameter-independent competition index were used to describe the competition environment for each individual tree in the plot. The over-topping shade index was calculated as in Equation 5.

$$S_I = \Sigma \frac{D_{neighbour}}{D_{tree} \times dist} \quad (5)$$

where

S_I = over-topping shade index
$D_{neighbour}$ = diameter of a neighbour tree
D_{tree} = diameter of a tree for which shade index was calculated
dist = distance between two trees (m)

Diameter-independent competition index was derived by modelling the relationship between calculated over-topping shade index (S_I) and diameter of tree which the shade index (D_{tree}) was calculated from (Equations 6 and 7 respectively).

$$S_I = \frac{b_0}{b_1 + D_{tree}} + b_2 \quad (6)$$

$$D_D = S_I - \frac{b_0}{b_1 + D_{tree}} + b_2 \quad (7)$$

where

D_D = diameter-independent competition index

b_0, b_1, b_2 = model parameters

Data screening and modelling

Data screening was carried out as in Vanclay (1994):

(1) Plotting raw data and fitting of regression line—The calculated periodic annual diameter increments were checked for errors against the explanatory variable (tree diameter). Data errors that are caused by typing mistakes were corrected and remained in the analysis.

(2) Residual plot—Residuals (difference between the observed and predicted values) versus predicted values were plotted to reveal any trend not explained by the model, and to identify outliers or extreme values and further transformations that should be considered for the dependent variables. Residuals or the predicted values showing extreme values from the normal trend were excluded (Vanclay 1994). These trees we not used in fitting the models.

Assuming that growth was non-linear, the diameter increment of the species was fitted by the method of ordinary least square (OLS) (Vanclay 1991, 1994, West 1995). The OLS assumes equal variance and unbiased estimates of the model parameters if the observations are independent and have equal variances. If the assumptions are not met, or variation increases with increasing d, and in the adjustment of the heterogeneity of variance, the P_{obs}, i.e. the response variable was either transformed or weighted to alter the relationship between explanatory variables as in Martin and Rafael (2004), Wan Razali (1988) and Khali Aziz and Azmy (1994). A problem arose with the logarithmic transformation of increment data because of the presence of zero periodic annual diameter increments. The data contained significant observations of zero increments and it was considered necessary to include these in the regression. An offset value was added to the dependent variables (Wan Razali 1988, Vanclay 1989a, Gourlet-Fleury *et al.* 2002). The transformation of P_{obs} having zero increments was in the form of ln (P_{obs} + 0.3). For the weighted model, it was obtained by multiplying both sides of the model equation by d^2. The model equations for both transformed and weighted are in Equations 8 and 9.

$$\mathrm{In}(P_{obs} + 0.3) = \beta_0 + \beta_1 d + \beta_2 d^2 + \beta_3 O_T + \beta_4 G + \beta_5 E_L + \beta_6 S_D + \beta_7 S_P + \beta_8 D_D + \beta_9 S_I \quad (8)$$

$$P_{obs}/d^2 = \beta_0 + \beta_1 d + \beta_2 (1/d^2) + \beta_3 O_T + \beta_4 G + \beta_5 E_L + \beta_6 S_D + \beta_7 S_P + \beta_8 D_D + \beta_9 S_I \quad (9)$$

where

β_0 = regression intercept

$\beta_{1 \text{ to } 9}$ = regression coefficients

O_T = over-topping basal area (m^2 ha^{-1})

G = basal area ha^{-1}

E_L = elevation (m)

S_D = stand density

S_p = slope (%)

S_I = over-topping shade index

The actual predicted response variable was then transformed as in Equation 10 and for the weighted by multiplying both sides of the weighted model equation by d^2.

$$P' = \exp^{(\beta_0 \ldots \beta_9)} - 0.3 \quad (10)$$

where

P' = predicted periodical annual diameter increment (cm $year^{-1}$)

The periodic annual diameter increments were then subjected to multiple regression analysis, SAS/STAT 1989 PROC REG Procedure where the coefficient of determination (r^2) was used as the indicator of regression accuracy. Residual analyses were used to determine the lack of fit, non-homogeneous variance or heteroscedasticity and bias (West 1980, Wan Razali 1988, Vanclay 1994, Alder 1995, Ong & Kleine 1995).

Analyses of data

Statistical analyses to determine the relationship between response and independent variables were analyzed using upward SAS/STAT 1989 PROC REG Stepwise Procedure. The Duncan's multiple range test was used to determine differences between means. The mean and standard error of P_{obs} was calculated using SAS/STAT 1989 PROC Summary. The upper level distribution of the periodic increments was determined using SAS/STAT 1989 PROC Univariate.

Model comparison

Models are based by their goodness of fit as measured by r^2, mean of the residuals, root mean square error or standard error of fitted regression. The usual index of fit, i.e. the root mean square error, can only be used to compare models that have the same response or dependent variable (Furnival 1961). The index of fit of untransformed function is the standard error of the regression. As an alternative Vanclay (1994) and Philip (1994) suggested the Furnival index (Furnival 1961) as a basis of model comparison. The index adjusts the standard error of the regression in order to facilitate the comparison. The Furnival index (FI) is calculated by multiplying the standard error of the fitted regression (root mean square error) by the geometric mean and the reciprocal of the derivative of the transformed variable and weighted with respect to the untransformed variable.

RESULTS

Table 1 gives the summary of mean values of all variables for each plot including slope, elevation, stand density, basal area, independent variables and competition indices within the study area. The slope ranged from as low as 3.9% to as high as 46.4%, while the elevation ranged between 78.9 and 110.3 m asl. Plots 2 and 6 had the lowest stand density and as a result, had the highest observed mean periodic annual diameter increments. For the basal area, plot 5 was the highest as the plot contained the highest number of trees ha^{-1}. The competition indices (diameter independent, shade index and over-topping basal area) were calculated using the SYMFOR modelling framework. A total of 876 P_{obs} observations were screened, of which 18 were outliers and discarded. The remaining increments (858) including zero increments and small negative decrements were used in the analysis. Distribution of the scatter of points indicated that P_{obs} was 0.28 cm rose from zero for the smallest trees to a maximum as the size class increased (Figure 1). Means of the P_{obs} after the screening and the upper range of P_{obs} between observation periods (1997 to 2000) are given in Table 2. The P_{obs} in plots 2 and 6 were significantly higher than the rest of the plots at $p < 0.05$.

Modelling

The fitted regression models developed from this

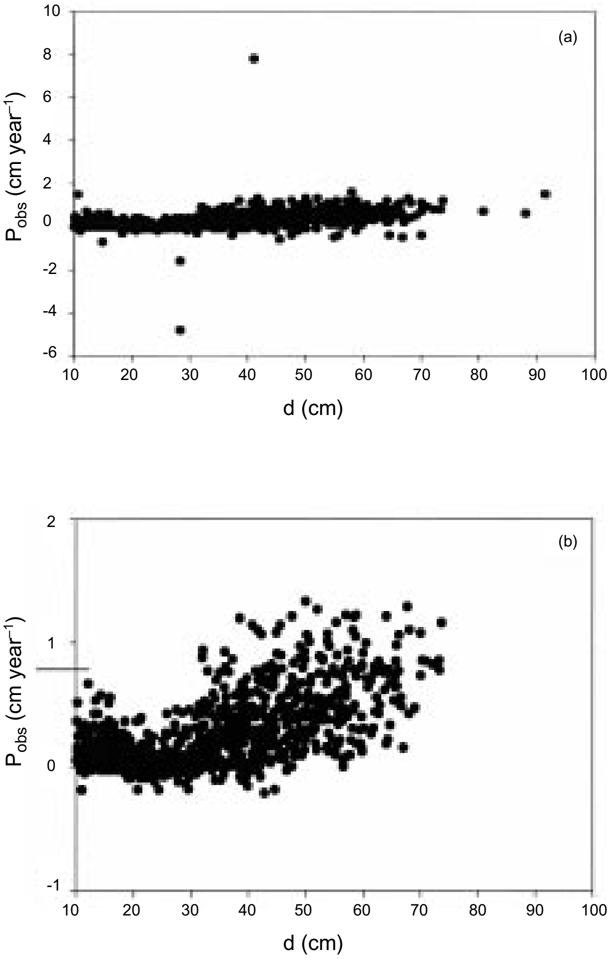

Figure 1 Distribution of observed periodic annual diameter increments (P_{obs}) with d for plots (a) before screening and (b) after screening between 1997 and 2000 (858 observations)

Table 1 Mean values of explanatory variables for growth modelling of *Dryobalanops sumatrensis* in Bukit Lagong Forest Reserve

Plot	Slope (%)	Elevation (m)	Stand density ha^{-1}	Basal area (m^2 ha^{-1})	Index 1	Index 2	Over-topping basal area
1	3.9	92.8	321	321	0.9921	6.7948	0.2030
2	16.7	78.9	161	161	0.3726	3.5984	0.1559
3	26.6	110.3	318	318	1.1915	7.3014	0.2973
4	46.4	104.1	258	258	0.7858	5.8119	0.2279
5	4.3	96.4	557	557	1.7521	8.3821	0.2450
6	41.2	106.1	184	184	0.4940	3.0225	0.2056

Indices 1 and 2: distance independent competition index and over-topping shade index respectively relationship are as shown in Table 3 and Equations 11 and 12.

$$\ln(P_{obs} + 0.3) = -0.48829 + 0.00023664*d^2 - 0.29010O_T - 0.02025G + 0.00303E_L - 0.00315S_P \quad (11)$$

$$P_{obs} = 0.2735 - 0.0002*d^2 + 0.000007E*d^2 - 0.000005S_P*d^2 - 0.00009S_I*d^2 \quad (12)$$

So far, two growth models had been fitted and the problem was to determine the most appropriate between alternative models. Figures in Table 3 show the calculated coefficient of determination and Furnival index of fit for each model used in the prediction of periodic annual diameter increment. It may be concluded that the transformed model is better than the weighted in the order of Furnival index values. The outputs from the transformed model showed that d^2, O_T, G, E_L and S_P explained a significant proportion of the variation in the periodic annual diameter increment transformed at 0.23 cm. The F statistic for the model was significant, indicating that this model explained a significant proportion of the variation in the data. Overall, the models explained 36.74% of the variation. The elevation ($p > 0.05$), distance diameter independent competition index and over-topping shade index did not contribute in explaining the variation in P_{obs}. Test of the null hypothesis that the true values of these variables were not significantly different from zero and the contribution of variables to the prediction of P_{obs}, the probabilities for the test is explained as shown in Table 3. A diameter of 1 cm contributed 0.015 cm (calculated from the table from the square root of d^2) to the predicted P_{obs}, if all other variables were held fixed. Over-topping basal area of 1 m^2 reduced 0.29 cm of the predicted P_{obs}, if all other variables were held fixed. From the table, the transformed model had the lowest Furnival index; thus it may be concluded that this model is the most appropriate.

Table 2 Mean periodic annual diameter increments (after screening) by plots, the standard error, from 1997 to 2000 (858 observations)

Plot	Mean	Mean
1	0.30 ± 0.01b	0.30 ± 0.01b
2	0.39 ± 0.03a	0.39 ± 0.03a
3	0.25 ± 0.02b	0.25 ± 0.02b
4	0.25 ± 0.02b	0.25 ± 0.02b
5	0.21 ± 0.02b	0.21 ± 0.02b
6	0.40 ± 0.04a	0.40 ± 0.04a
Mean	0.28 ± 0.01	0.28 ± 0.01

Means with same letter are not significantly different at $p < 0.05$ as determined by Duncan's multiple range tests. Means are reported ± 1 standard error.

Table 3 Estimation of the parameters, p values, r^2 and Furnival index

Variables	Estimates	Pr > F	r^2	Furnival index
	Transformed		0.3674	0.2109
β_0	-0.48829	0.0166		
d^2	0.00024	< 0.0001		
O_T	-0.29010	0.0009		
G	-0.02025	0.0066		
E_L	0.00303	0.1471		
S_p	-0.00315	0.0021		
	Weighted		0.2956	0.6022
β_0	0.2735	0.1719		
d^2	-0.0002	0.0001		
E_L d^2	0.000007	0.0001		
S_p d^2	-0.000005	0.0001		
S_I d^2	-0.00009	0.0001		

Figure 2 shows that the regression lines of weighted and transformed function, with the latter predicting the increments at decreasing rate for larger trees. The fitted regression lines plotted against observations from 1997 to 2000 showed that the logarithmic regression lines (Figure 3b) reflected the pattern of the data and produced an apparent better fit (Figure 2). However, the residuals in all plots, which were randomly distributed, showed that heteroscedasticity was present and was actually rather large for predicted P_{obs} above 0.5 cm $year^{-1}$ (Figure 3).

DISCUSSION

The residual generated from data with multiple measurements are not independent, thus contrary to assumptions of the independence of the values of residuals required for ordinary least square regression (West 1995). However, it is applicable as the purpose this study was to predict the future of *D. sumatrensis* and not about testing hypotheses on fitted regression. In the prediction of P_{obs}, the initial tree diameter, basal area, over-topping basal area and slope explained a significant proportion of the variation to the increment at 36.7% ($p < 0.05$, Table 3). Similar results were obtained by Ong and Kleine (1995) who used a DIPSIM model to study the effects of initial tree size, stand basal area and over-topping basal area on the increment of dipterocarps and non-dipterocarps. They reported negative values for stand basal area and over-topping basal area, indicating significant effects of competition indices on the growth. Competition indices, stand basal area and over-topping basal area are useful in growth modelling in plantation forests (Vanclay 1989a, b, 1991). These coefficients of

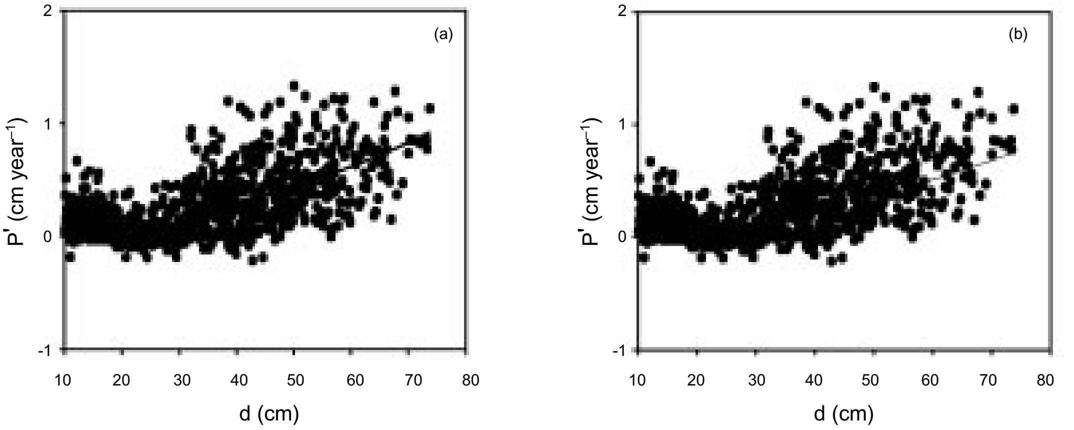

Figure 2 Scatter diagrams of predicted periodic annual diameter increment against diameter with regression lines. The models fitted (a) weighted and (b) transformed.

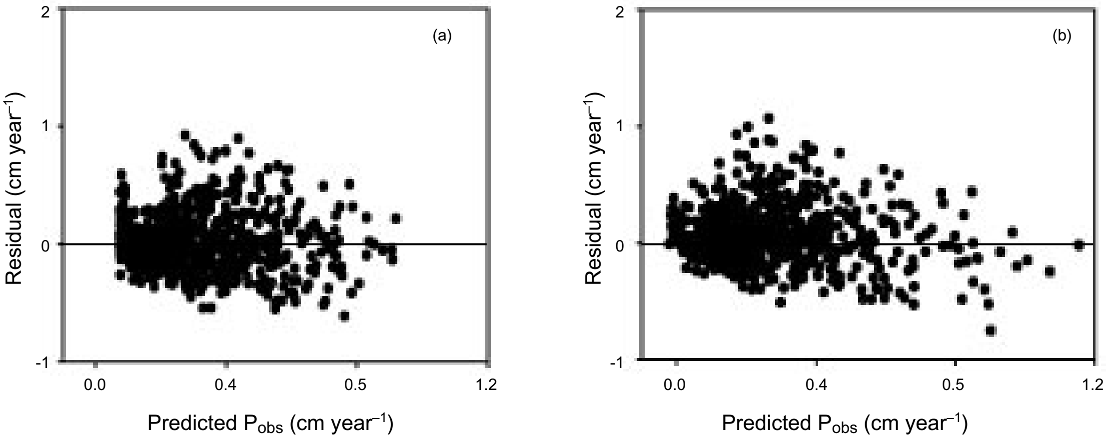

Figure 3 Residuals against the predicted periodic annual diameter increment. Models fitted (a) weighted and (b) transformed.

the estimated stand basal area and over-topping basal area are expected to show negative values.

Besides predicting growth, the model can also be used to explain some of the variations in growth rate of the species. For simple quadratic model with only d and d^2 as explanatory variables, positive coefficient may be obtained, meaning that the model predicts ever-increasing increments for larger and larger trees, which is biologically untenable. This model may provide reliable prediction of periodic diameter growth over a limited range of diameter, but it is clearly unsuitable for trees with large diameters and so it is not useful for long-term extrapolation.

It has been reported that diameter independent competition index and over-topping shade index were the main indices affecting tree growth (Phillips & van Gardingen 2001b). However, in this study, the competition indices of basal area per ha and over-topping basal area were more significant in explaining the variation of P_{obs}, as demonstrated by the model. The results were negatively biased as indicated by the positive mean residual (the difference between observed and predicted) of 0.05 cm, a clear indication of under-estimation by the model. For tree growth modelling studies, the ideal results should be unbiased or have zero mean residuals with no consistent trends left unexplained for the dependent variables in the model (West 1980, Alder 1995).

The tree elevation offered no improvement to the model prediction. The elevation range (78.9 to 110.3 m) of the study plots in Bukit

Lagong Forest Reserve were well within the range of its ecological distribution between 50–300 m asl and limited range had no significant effects on growth rate. *Dryobalanops sumatrensis* is generally common on land above 50 m contour level and in association with hilly areas (Lee 1967, Wong *et al.* 1987). However, it has been shown that tree elevation affected the density and basal area of *Dacryodes excelsa*-dominated rain forest in Puerto Rico (Basnet 1992).

CONCLUSIONS

From the growth modelling of normal plantation-grown *D. sumatrensis*, the following was observed:

(1) Transformed dependent variable using natural logarithm of P_{obs} gave better fit than weighted P_{obs} as indicated by the Furnival index.

(2) Inclusion of competition indices (overtopping basal area, basal area, stand density, distance independent, shade competition) and environmental variables (slope and elevation) in the growth model was useful in determining the significant factors that contributed to the proportion of variation in diameter increment.

(3) Overall results of the modelling were negatively biased and underestimated the P_{obs} of the species.

(4) The model explained 36.7% of the variation, which meant that there were other factors that influenced the growth of the species. Modifications to include additional environmental factors such as climatic fluctuations (rainfall and evapotranspiration), canopy openness and availability of light should be considered.

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