MIXED-EFFECTS MODELS FOR PREDICTING EARLY HEIGHT GROWTH OF FOREST TREES PLANTED IN SARAWAK, MALAYSIA

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Received June 2014

WAN RAZALI WM, ABDUL RAZAK T, MOHAMAD AZANI A & KAMZIAH AK. 2015. Mixed-effects models for predicting early height growth of forest trees planted in Sarawak, Malaysia. Total height growth models as a function of basal tree diameter at 10 cm above ground (D_{10}) for five indigenous species in Sarawak, namely, *Calophyllum sclerophyllum, Dryobalanops beccarii, Shorea mecistopteryx, Shorea leprosula* and *Shorea brunnescens,* were developed using mixed-effects models. A mixed-effects model is an extension of a random-coefficient regression in which fixed-effect coefficients are included to account for variations between and correlations within tree species, and is known to produce consistent estimates of the fixed coefficients and their standard errors. Linear, nonlinear, logistic and Chapman–Richards mixed-effects models were used to fit total tree height to D_{10}. Species were treated as random-effect and D_{10} fixed-effect in the models. Based on smallest value of Akaike Information Criterion and Bayesian Information Criterion, the linear model $H = (\beta_0 + b_0) + (\beta_1 + b_1)\ D_{10}$ indicated the best fit for all five species. Availability of height growth model helps in the early stage of species selection, whereby height growth is a dominant factor in choosing a species for rehabilitation programme, thus ensuring high species productivity and increased financial viability of the programme.

Keywords: Akaike Information Criterion, Bayesian Information Criterion, indigenous timber species, rehabilitation programme

INTRODUCTION

Two of the most critical environmental scenarios facing the world today are anticipated increase in temperature (climate change scenario) and loss of forest biodiversity (biodiversity scenario). Reforestation has often been proposed at national and international fora and meetings as a means to negate these two scenarios (IPCC 2001, Chua et al. 2007). Afforestation and/or reforestation is one way to increase or maintain forest area. Biodiversity will also be increased by planting multiple tree species in a forest area. Rehabilitation of forests with indigenous species now becomes an important aspect of forest conservation (Miyawaki 1992, Mohamad Azani 1995). To rehabilitate degraded tropical rainforest, quantitative information on growth performance of some potential indigenous species is important before one embarks on any big scale programme (Mohd Zaki et al. 1993, Mohamad Azani et al. 2001).

Many statistical techniques are available for developing growth model or growth function of trees. Mixed-effects models have received great attention for the past 40 years because of the flexibility they offer in handling data that arise in many areas of investigation (Pinheiro 1994). A mixed-effects model is an extension of a random-coefficient regression model in which fixed-effect coefficients are also included in the model to account for variations between individuals and correlations within individuals. In other words, when a model has both fixed-effect and random-effect, then the model is called a mixed-effects model (Budhathoki 2006, Wu 2010). Mixed-effects models estimate both fixed and random coefficients simultaneously for the same model, providing consistent estimates of the fixed coefficients and their standard errors. Mixed-effects model approach is a statistical technique that has been used in many fields, generating improvement in coefficient estimation (Calegario et al. 2005). Mixed-effects models have wide applications in areas such as agriculture, forestry, biology, ecology, biomedicine, sociology, economics and pharmacokinetics (Pinheiro & Bates 1998).

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In forestry, studies using mixed-effects models are relatively recent. As a pioneer, Biging (1985) managed to improve the estimates of site index curve using a varying-parameter model. In another approach, Lappi and Bailey (1988) described the use of nonlinear mixed-effects growth curve based on Richards model, which was fitted to predict dominant and codominant tree height, both at the plot and individual tree levels. Gregoire et al. (1995) used a mixed-effects model to account for correlation due to grouping in data structures that commonly occurred in forestry applications. They cited lack of easily available and user-friendly software as reason why there was still not much application of mixed-effects models in forestry at that time. Other studies based on mixed-effects models have been published in forestry (Zhang & Borders 2004, Budhathoki et al. 2008, Bueno-López & Bevilacqua 2012, Condés et al. 2013, Li & Jiang 2013).

The objective of this investigation was to develop total height growth model for each of the five indigenous species planted in Sarawak, namely, *Calophyllum sclerophyllum, Dryobalanops beccarii, Shorea mecistopteryx, Shorea leprosula* and *Shorea brunnescens*. Availability of height growth model will help in overcoming species selection process. The model is based mainly on early total height growth performance. This ensures proper selection of species to be planted from the very start of a reforestation programme and to increase site–species productivity and financial viability of the programme.

MATERIALS AND METHODS

Study site

This investigation was conducted at the Universiti Putra Malaysia (UPM)–Mitsubishi Forest Rehabilitation Project area at UPM Bintulu, Sarawak, Malaysia (Figure 1). The joint research project started in July 1991 between UPM and Yokohama National University, Japan on a 47.5-ha forest site at UPM Bintulu campus, Sarawak. The project was supported by the Mitsubishi Corporation of Japan. The data used in this investigation were from a permanent growth plot within the project forest area. The

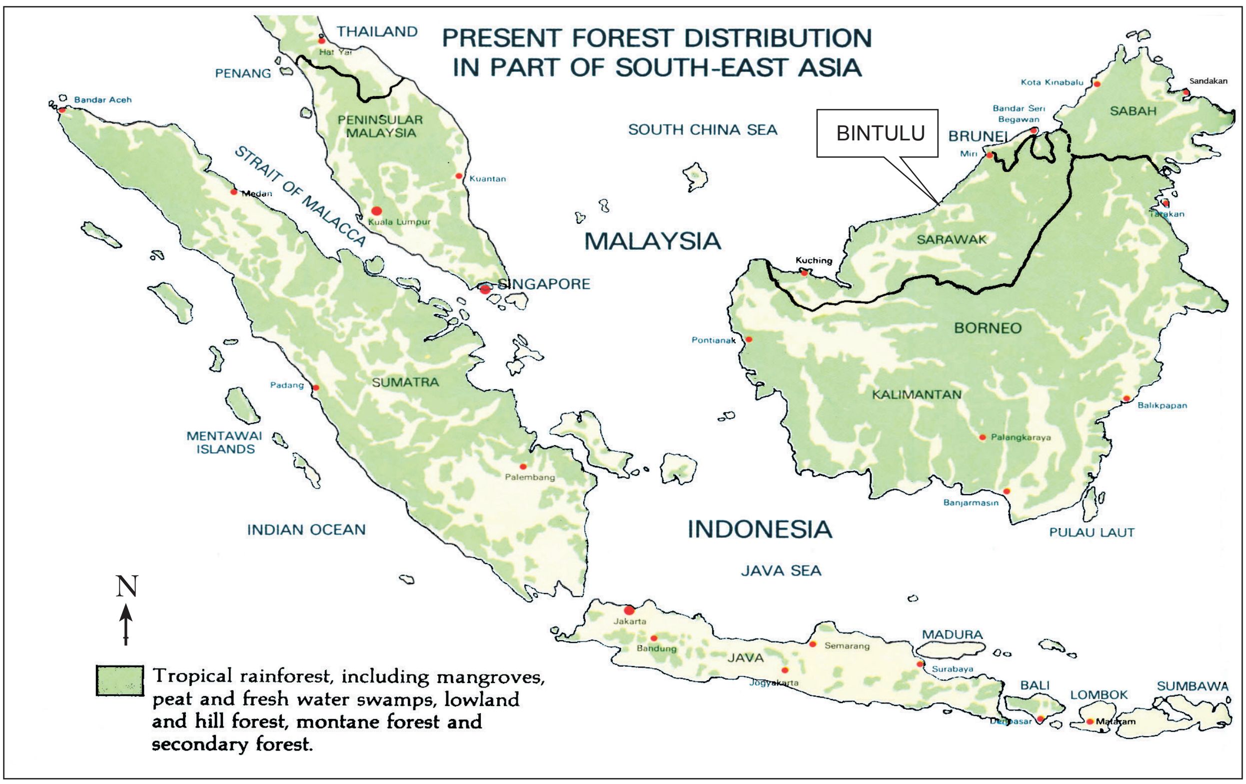

Figure 1 General location of the study area; source: Rubeli (1986)

project initiated is an excellent example of a highly successful forest rehabilitation project on degraded area. The data came from tree seedlings planted in a 50 m × 5 m plot that was established in June 1991. Open planting method was employed. The planted seedlings mimicked a compact stand of natural forest, equivalent to kerangas forest.

Seedlings were planted randomly in the permanent growth plot with close spacing of 3 seedlings m^{-2}. Dense planting was intended to create competition among seedlings, hence developing them into tall and strong individuals and the fittest continued growing. Dead seedlings were replaced to maintain species composition and competition among seedlings. Mulching materials (*Imperata cylindrical* and *Ischemum* spp.) were placed on the surface of the plot to reduce soil erosion, encourage retention of soil moisture and discourage incoming weeds. The mulching materials were secured to the surface using Manila rope. The mulching materials were also intended as a source of nutrients. Fertiliser containing N, P, K was applied in the first 3 months after planting and weeding was done.

Species and data measurement

At the time of plot establishment, there were a total of 653 tree seedlings comprising 21 species (Table 1). The choice of species was mainly based on their ecological suitability—all species were indigenous and known to grow within the project forest area before the area became degraded. After planting was completed, all trees were enumerated in August 1991 and their diameters at 10 cm above ground and total height measured and re-measured until May 2007 at intervals of 2 months until 1993 and 6 months from 1994 until May 2007.

Due to high mortality, only five species were considered suitable for model development as each species had more than 50 trees surviving—the minimum number of trees we considered as having sufficient sample for

Table 1 Species list in the 50 m × 5 m research plot at Universiti Putra Malaysia, Bintulu Campus, Sarawak

No.	Vernacular name	Scientific name	Initial number of tree seedlings planted (n = number used for modelling)
1	Bintangor jangkang	*Calophyllum sclerophyllum*	104 (n = 73)
2	Chengal paya	*Hopea pentanervia*	2
3	Durian	*Durio zybethinus*	3
4	Engkabang jantung	*Shorea macrophylla*	8
5	Kapor	*Dryobalanops beccarii*	92 (n = 84)
6	Kawi	*Whit. moultonianum*	4
7	Kelampu	*Sandoricum koetjape*	2
8	Luis	*Hopea kerangensis*	46
9	Meranti pitis	*Shorea ovata*	27
10	Meranti kawang burung	*Shorea mecistopteryx*	96 (n = 74)
11	Meranti lun	*Shorea multiflora*	6
12	Meranti tembaga	*Shorea leprosula*	68 (n = 60)
13	Meranti batu	*Shorea dasyphylla*	31
14	Meranti sarang punai	*Shorea parvifolia*	10
15	Merawan	*Hopea beccariana*	44
16	Pelajo	*Pentaspadon motleyi*	6
17	Selangan batu	*Shorea brunnescens*	96 (n = 72)
18	Sengkuang	*Dracontomelon dao*	1
19	Tongkat ali	*Euricoma longifolia*	2
20	Ubah	*Eugenia hoseana*	3
21	Upun	*Upuna borneensis*	2

model development. Five species with a total of 363 trees were selected for model development as shown in Table 2. Trees selected covered as much as possible variation of diameter sizes at 10 cm above ground and of total height measurements from 1991 till 2007. The descriptive statistics of sample trees are shown in Table 3.

Mixed-effects models

For each species, the following mixed-effects models were used to develop total height growth as a function of tree diameter (cm) at 10 cm above ground:

(Model 1): linear mixed-effects model:

$$H_{ij} = (\beta_0 + b_0) + (\beta_1 + b_1)\ D_{ij} + e_{ij} \qquad (1)$$

(Model 2): nonlinear mixed-effects model:

$$H_{ij} = (\beta_0 + b_0)\ D_{ij}^{\ (\beta_1 + b_1)} + e_{ij} \qquad (2)$$

(Model 3): logistic mixed-effects model:

$$H_{ij} = \frac{\beta_0 + b_0}{1 + \exp[-(D_{ij} - \beta_1)/\ \beta_2]} + e_{ij} \qquad (3)$$

(Model 4): Chapman–Richards mixed-effects model:

$$H_{ij} = (\beta_0 + b_0)\,[1 - \exp(-\beta_1 D_{ij})]^{\ (\beta_2 + b_2)} + e_{ij} \qquad (4)$$

where H_{ij} = total height (cm) of the i^{th} tree of the j^{th} species; D_{ij} = basal diameter (cm) at 10 cm above ground of the i^{th} tree of the j^{th} species; β_0, β_1 and β_2 = fixed-effect coefficients; b_0, b_1 and b_2 = random-effect coefficients associated with the j^{th} species and e_{ij} = random error of the model.

The species were treated as random-effect in all these models. Statistical procedures in the SAS® 9.2 program were used—PROC MIXED for linear mixed-effects model (Model 1), and PROC NLMIXED for nonlinear mixed-effects models (Models 2, 3 and 4).

Table 2 Five indigenous timber species selected for height growth model development

Species	Common name	Family	n
Calophyllum sclerophyllum	Bintangor jangkang	Guttiferae	73
Dryobalanops beccarii	Kapur bukit	Dipterocarpaceae	84
Shorea mecistopteryx	Meranti kawang burung	Dipterocarpaceae	74
Shorea leprosula	Meranti tembaga	Dipterocarpaceae	60
Shorea brunnescens	Selangan batu	Dipterocarpaceae	72
		Total	363

Table 3 Descriptive statistics of all sample trees by species

Species	Variable	n	Mean	Max	Min	Standard deviation
Calophyllum sclerophyllum	Height (cm)	73	43.23	201.00	9.20	39.92
	Diameter(cm)	73	0.56	1.75	0.25	0.37
Dryobalanops beccarii	Height (cm)	84	107.34	267.00	18.70	72.62
	Diameter(cm)	84	1.51	3.97	0.21	1.16
Shorea mecistopteryx	Height (cm)	74	72.16	211.00	20.40	51.83
	Diameter(cm)	74	1.17	3.50	0.20	0.78
Shorea leprosula	Height (cm)	60	79.63	260.00	22.30	61.83
	Diameter(cm)	60	1.36	5.57	0.24	1.29
Shorea brunnescens	Height (cm)	72	94.18	262.00	41.02	21.30
	Diameter(cm)	72	0.89	2.94	0.22	0.75

Model comparison criteria

The goodness-of-fit criteria of Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) having the smallest value were used to select the best fit total height growth model. AIC and BIC have been reported to be useful for evaluating goodness-of-fit of different mixed-effects models (Gregoire et al. 1995, Pinheiro & Bates 2000, Tao 2002) as follows:

$$AIC = -2(\text{log-likelihood}) + 2(\text{no. of parameters}) \quad (5)$$

$$BIC = -2(\text{log-likelihood}) + (\text{no. of parameters}) \times \log(N) \quad (6)$$

where N = total number of observations used to fit the model.

AIC is equivalent to the C_p-statistic and adjusted r^2 in ordinary regression model in the sense that AIC takes the number of parameters into account (Gregoire et al. 1995). A model with the smallest AIC and BIC values is considered the best fit (Gregoire et al. 1995, Pinheiro & Bates 2000, Budhathoki 2006).

The final model for each species was also evaluated based on the appropriate value of other goodness-of-fit criteria such as coefficient of determination (r^2), root mean square error (RMSE) and mean absolute error (MAE) to assess the predictive capability of the model (Cochran 1977). However, because of the closeness of r^2, RMSE and MAE values between the four mixed-effects models, the values of AIC and BIC were used as the final criteria in selecting the best fit model.

Model checking

Although models were selected based on AIC and BIC, the selected models were further evaluated based on the analysis of residuals. Plots of residuals against predicted values and against individual explanatory variable could reveal any poor fit of the data to the model or the presence of outliers if any, as follows:

$$e_i = Y_i - \hat{Y}_i = 1, 2, \ldots, < n \quad (7)$$

where e_i = residual, Y_i = observation value and $\hat{Y}_i$ = corresponding predicted value.

Analysis of variance and least significant difference tests

Analysis of variance (ANOVA) and least significant difference (LSD) tests were utilised in order to detect any significant difference in models between the five species. Based on Abdi and Williams (2010), the value of the t-statistics evaluating the difference between groups a and a' (denoting different species) is:

$$t = \frac{M_{a+} - M_{a'+}}{\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)}} \quad (8)$$

where S_a and $S_{a'}$ = number of observations of the a^{th} group; M_{a+} = mean of group a; $M_{a'}$ = mean of group a' and $MS_{S(A)}$ = mean square error (i.e. within group error).

This t-statistic follows Student's t-distribution with N – A degrees of freedom. The ratio t would therefore be declared significant at a given level α obtained from the t-distribution and denoted $t_{v,\alpha}$ (where v = N – A is the number of degrees of freedom of the error; N = total number of observations; A = total number of groups). Rewriting this ratio shows that the difference between the means of groups a and a' will be significant if:

$$|M_{a+} - M_{a'+}| > LSD = t_{v,\alpha}\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)} \quad (9)$$

and the difference between the means of groups a and a' will be not significant if:

$$|M_{a+} - M_{a'+}| < LSD = t_{v,\alpha}\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)} \quad (10)$$

A (1 – α) 100% confidence limit $|M_{a+} - M_{a'+}|$ of observations per group is as follows:

$$|M_{a+} - M_{a'+}| \pm LSD = t_{v,\alpha}\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)} \quad (11)$$

RESULTS AND DISCUSSION

Model comparison

Based on AIC and BIC and other goodness-of-fit statistics r^2, RMSE and MAE, the linear mixed-effects model (Model 1) indicated the best fit for predicting total height of the five indigenous timber species planted in Sarawak (Table 4). Model 1 had the smallest value of AIC (3106.0) and BIC (3104.8). Model 1 also had the smallest value of RMSE (16.48), MAE (11.2394) but a similar r^2 (93.39%) with Model 2. However, AIC and BIC favoured Model 1 as the best fit among the four models tested.

Coefficient estimate of best fit model (Model 1)

Tables 5 and 6 respectively show the value of fixed-effect coefficients (β_0, β_1) for all species and random-effect coefficients (b_0, b_1) for each species in Model 1. The fixed-effect and random-effect coefficients were estimated using restricted maximum likelihood (REML) method by the PROC MIXED procedure of the SAS® 9.2 program.

Table 7 indicates best fit equations for predicting height using Model 1 for each species. The graphs of the fitted curve (equation from Table 7) for each species are shown in Figure 2.

Residual plot analysis

Residual plots analyses (Figures 3 and 4) showed no clear evidence of variance heterogeneity. The variance of residual was distributed almost homogeneously over the full range of predicted values. There was no systematic pattern in the variation of residual.

Table 4 Comparison of criteria and goodness-of-fit statistics between models

Model	– 2 Log	AIC	BIC	MAE	RMSE	r^2
1	3100.0	**3106.0**	**3104.8**	11.2394	16.48	**0.9339**
2	3109.8	**3121.8**	**3119.4**	11.5332	16.49	**0.9339**
3	3193.2	3203.2	3201.3	14.0633	18.95	0.9127
4	3175.1	3189.1	3186.4	13.1956	17.65	0.9243

AIC = Akaike Information Criterion, BIC = Bayesian Information Criterion, MAE = mean absolute error, RMSE = root mean square error, r^2 = coefficient of determination

Table 5 Fixed-effect coefficients of Model 1

Fixed-effect coefficient for all species	Estimate	Standard error	t-value	Pr > |t|
β_0	7.2305	5.7221	1.26	0.2750
β_1	70.7110	9.5328	7.42	0.0018

Table 6 Random-effect coefficients of Model 1

Random-effect coefficient	Species	Estimate	Standard error	t-value	Pr > |t|
b_0	*Calophyllum sclerophyllum*	-18.0372	6.2775	-2.87	0.0043
b_1	*Calophyllum sclerophyllum*	25.8087	10.2962	2.51	0.0126
b_0	*Dryobalanops beccarii*	8.3429	6.1382	1.36	0.1750
b_1	*Dryobalanops beccarii*	-10.1483	9.6042	-1.06	0.2914
b_0	*Shorea mecistopteryx*	-6.6726	6.2692	-1.06	0.2879
b_1	*Shorea mecistopteryx*	-9.4541	9.7073	-0.97	0.3308
b_0	*Shorea leprosula*	8.3756	6.1740	1.36	0.1758
b_1	*Shorea leprosula*	-23.9619	9.6134	-2.49	0.0131
b_0	*Shorea brunnescens*	7.9911	6.1477	1.30	0.1945
b_1	*Shorea brunnescens*	17.7556	9.7306	1.82	0.0689

Prediction of height

Table 8 indicates the predicted height (m) increment for every 1 cm of basal diameter increment using Model 1. Based on basal diameter 2–14 cm, the average predicted heights for every 1 cm increment of basal diameter of each species were: 0.857 m (*C. sclerophyllum*), 0.761 m (*D. beccarii*), 0.618 m (*S. mecistopteryx*), 0.623 m (*S. leprosula*) and 1.037 m (*S. brunnescens*). Based on the above, it could be concluded that the height (m) performance for every 1 cm of basal diameter increment of the five species was in the following order:

(1) *Shorea brunnescens* 1.037 m (highest)
(2) *Calophyllum sclerophyllum* 0.857 m
(3) *Dryobalanops beccarii* 0.761 m
(4) *Shorea leprosula* 0.623 m
(5) *Shorea mecistopteryx* 0.618 m (lowest)

Analysis of variance and least significant difference tests

ANOVA to detect if there was any difference of total height growth model between the five species is shown in Table 9. There was high significant difference between species.

In order to analyse the pattern of difference between means of height of any two species, the LSD test was carried out and the results are shown in Table 10. *Shorea leprosula* recorded one of the lowest height increments when planted in the open. This was in accordance with the findings of Mohamad Azani (1998) whereby *S. leprosula* planted under partial shade had higher growth

Table 7 Best fit equations for predicting total tree height using Model 1

Species	Equation*
Calophyllum sclerophyllum	H_{ij} = (7.2305 -18.0372) + (70.7110 + 25.8087) D_{ij}
Dryobalanops beccarii	H_{ij} = (7.2305 + 8.3429) + (70.7110 - 10.1483) D_{ij}
Shorea mecistopteryx	H_{ij} = (7.2305 - 6.6726) + (70.7110 - 9.4541) D_{ij}
Shorea leprosula	H_{ij} = (7.2305 + 8.3756) + (70.7110 - 23.9619) D_{ij}
Shorea brunnescens	H_{ij} = (7.2305 + 7.9911) + (70.7110 + 17.7556) D_{ij}

*General equation: $H_{ij} = (\beta_0 + b_0) + (\beta_1 + b_1) D_{ij} + e_{ij}$

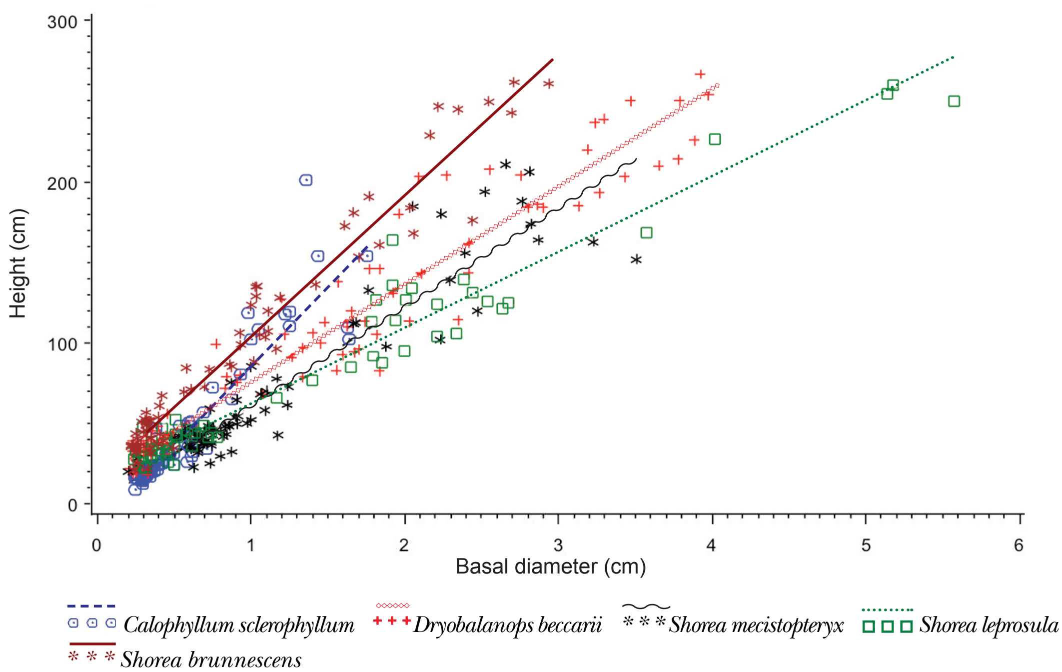

Figure 2 Observation and prediction curve using linear mixed-effects (Model 1)

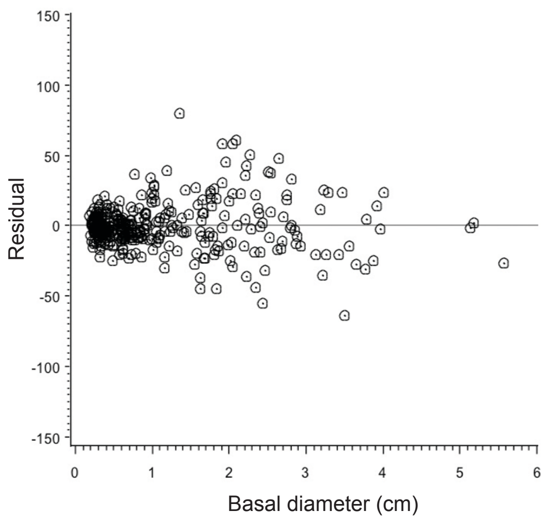

Figure 3 Residual versus predictor variable for linear mixed-effects model (Model 1)

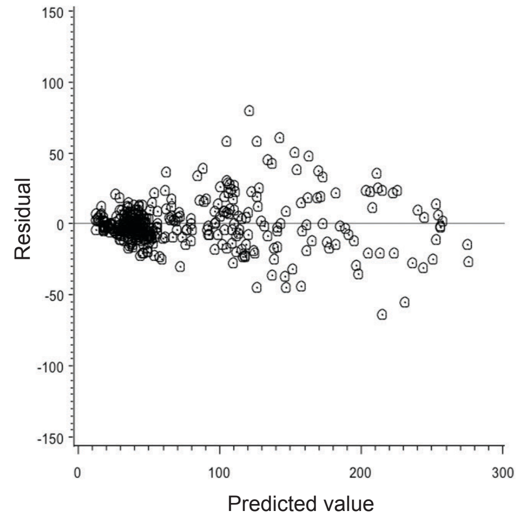

Figure 4 Residual versus predicted value for linear mixed-effects model (Model 1)

Table 8 Predicted height (m) increment for every 1 cm of basal diameter increment as predictor variable

Species	Basal diameter (cm)						
	2	4	6	8	10	12	14
Shorea brunnescens	2.07	4.15	6.22	8.30	10.37	12.44	14.52
Calophyllum sclerophyllum	1.71	3.43	5.14	6.85	8.57	10.28	12.00
Dryobalanops beccarii	1.52	3.04	4.57	6.09	7.61	9.13	10.65
Shorea leprosula	1.25	2.49	3.74	4.98	6.23	7.48	8.72
Shorea mecistopteryx	1.24	2.47	3.71	4.94	6.18	7.42	8.65

Table 9 ANOVA for height model

Source	df	Sum of squares	Mean square	F-value	Pr > F
Model	4	180492.756	45123.189	12.35	< 0.0001
Error	358	1308230.732	3654.276		
Total	362	1488723.488			

performance compared with those planted in the open. *Shorea leprosula* exposed to extreme heat and strong wind when planted in the open performed poorly (Arifin Abdu et al. 2004) as the species is only a light demander, i.e. some shade is required in the early growth of the species. Although *S. brunnescens* is also a light demanding species, planting them in dense spacing gave the species better growth compared with other species. Dense planting had induced early canopy closure and biologically controlled weed growth (Mohamad Azani et al. 2001) and hence faster height growth. *Shorea mecistopteryx*, on the other hand, is a shade tolerant species and therefore open planting had retarded its height (Mohamad Azani et al. 2003).

CONCLUSIONS

Based on AIC and BIC results, linear mixed-effects model was found to be the best fit for all the five species. As the height model developed made use of a limited range of diameter and height, its application beyond the original range

Table 10 Species height model comparison using least significant difference test

Species comparison	Difference between means	95% Confidence limit		Significance
Dryobalanops beccarii–Shorea brunnescens	13.164	-5.929	32.258	ns
Dryobalanops beccarii–Shorea leprosula	27.713	7.618	47.808	*
Dryobalanops beccarii–Shorea mecistopteryx	35.182	16.228	54.135	*
Dryobalanops beccarii–Calophyllum sclerophyllum	64.107	45.084	83.129	*
Shorea brunnescens–Shorea leprosula	14.549	-6.232	35.330	ns
Shorea brunnescens–Shorea mecistopteryx	22.017	2.338	1.697	*
Shorea brunnescens–Calophyllum sclerophyllum	50.942	31.196	70.688	*
Shorea leprosula–Shorea mecistopteryx	7.468	-13.184	28.121	ns
Shorea leprosula–Calophyllum sclerophyllum	36.394	15.677	57.110	*
Shorea mecistopteryx–Calophyllum sclerophyllum	28.925	9.314	48.536	*

*Significant at $\alpha = 0.05$ level, ns = not significant

of data and outside the range of Bintulu area needs further testing and validation before the model can be adopted.

ACKNOWLEDGEMENTS

We thank S Ahmad from the Institute for Mathematical Research, UPM for advice and guidance on the use of statistical procedures in the SAS® 9.2 program. This investigation was supported by a research grant from UPM.

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