CROWN DIAMETER PREDICTION MODEL FOR PLANTATION-GROWN *NEOLAMARCKIA CADAMBA*

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AHMAD ZUHAIDI Y. 2013. Crown diameter prediction model for plantation-grown *Neolamarckia cadamba*. This paper reports on the development of a prediction model for plantation-grown *Neolamarkcia cadamba* using crown diameter as the main parameter. Data were collected from private plantations in Sandakan, Sabah; Sabah Softwood Limited in Tawau, Sabah; WTK Group of Plantations in Sibu, Sarawak and plantations in Setul Forest Reserve, Negeri Sembilan. The plantations were 4 and 10 years old. The ordinary least square method was used in analyses with six models using transformed, untransformed and weighted crown diameter as the response variables as well as diameter at breast height (dbh) and dbh^2 as the independent variables. With values of coefficient of determination (r^2) and standard error of fitted regression (or root mean square error), the Furnival index (FI) obtained was used as the final selection criterion for the best fitted model. The results indicated that model 5, having weighted response variable, gave the lowest FI at 0.017 and was thus selected as the most appropriate crown diameter prediction model for *N. cadamba*.

Keywords: Transformed models, weighted models, Furnival index, potential final crop trees

AHMAD ZUHAIDI Y. 2013. Model unjuran diameter silara bagi *Neolamarckia cadamba* yang ditanam di ladang. Kertas kerja ini melaporkan tentang pembangunan model unjuran diameter silara bagi *Neolamarckia cadamba* yang ditanam di ladang. Data diperoleh daripada ladang swasta di Sandakan, Sabah; Sabah Softwood Berhad di Tawau, Sabah; Ladang Kumpulan WTK di Sibu, Sarawak dan Hutan Simpan Setul di Negeri Sembilan. Kesemua dirian berusia antara 4 tahun hingga 10 tahun. Kaedah kuasa dua terkecil biasa digunakan untuk menguji enam model dengan data yang ditransformasi, tanpa transformasi dan diameter silara berpemberat sebagai pemboleh ubah bersandar serta diameter pada aras dada (dbh) dan dbh^2 sebagai pemboleh ubah tak bersandar. Dengan nilai pekali penentuan (r^2) dan ralat piawai bagi regresi padanan (atau ralat punca min kuasa dua), indeks Furnival (FI) yang diperoleh digunakan sebagai kriteria pemilihan model yang sesuai untuk membuat unjuran. Keputusan menunjukkan bahawa model 5 yang menggunakan pemboleh ubah berpemberat memberi nilai FI terendah iaitu 0.017 dan dipilih sebagai model yang paling sesuai untuk unjuran diameter silara *N. cadamba*.

INTRODUCTION

The space for tree crown diameter is often defined as the horizontal distance above the ground surface area or crown projection area (O'Hara 1988). Each tree in a stand requires a definite area of crown space which, to an extent, is limited by the ground available surface and the direct neighbours of the tree that restrict lateral growth. The crown space concepts have been employed in growth modelling studies, based not only on the measure on the ground area or resources available to the individual tree but also as an index of competition and measurement on open-grown trees being used to predict potential increment in stem diameter (Krajicek et al. 1961, Faber 1991). The use of tree crown size as a variable in growth models has long been established for temperate species (Ayhan 1973) but not for subtropical species (Suri 1975). A study by Ahamd Zuhaidi (2009) showed the importance of crown size and its potential in improving the degree of accuracy and reliability of growth predictions.

Long-term studies on crown dynamics are generally lacking and data from which crown development models can be constructed are scarce. The general lack of information on tree crowns and their application in tree growth modelling is even more pronounced for tropical forests species. It is important that more allometric relationship be established between crown and tree diameter of different tropical species as this can generate new knowledge on crown diameter relationship of species which can provide a guide on various applications including estimation of optimum planting distance and possible potential crop density.

The study of plantation-grown *Neolamarckia cadamba* (Rubiaceae) was carried out to provide baseline information for facilitating the management of the species by developing growth models. This species is commonly found as naturally regenerated stands in many parts of Sabah and Sarawak forests and are being harvested for veneer manufacturing. Due to its fast-growing characteristics, this species has been selected as a plantation species under the Malaysian Timber Industry Board Plantation Programme in Malaysia (Ahmad Zuhaidi & Hashim 2010). This species together with other native species was intended for large-scale planting within a proposed rotation period of 15 years. The objective of this study was to examine the allometric relationship of plantation-grown *N. cadamba* by regression of curvilinear models between crown diameter and tree diameter at breast height.

MATERIALS AND METHODS

Materials

Study plots having one, two and three replicates were established in 4-year-old plantation-grown *N. cadamba* stands in Sandakan, Sabah (Kenangan Manis, private plantation); Immense Fleet Plantation, Kanowit, Sibu, Sarawak and Setul Forest Reserve, Negeri Sembilan, Peninsular Malaysia as well as in 10-year-old stand in Sabah (Sabah Softwood Limited, Tawau) (Figure 1). Details of the plots are shown in Table 1.

Figure 1   Geographical location of the study sites

Table 1   Details of the four study sites

	Sandakan	Tawau	Kanowit	Setul
Latitude (N)	5° 54'	4° 16'	2° 33'	2° 47'
Longitude (E)	118° 04'	117° 53'	111° 83'	101° 55'
Altitude (m)	25–30	78–80	100–180	75–250
Soil texture	Alluvial soil, riverine area	Loamy sand and clay	Loamy sand and clay	Light reddish, sandy loam
Terrain	Flat	Flat	Undulating	Undulating
Mean annual rainfall (mm)	2750–2900	1700–2040	270–3000	1900–2050
Mean annual temperature (ºC)	26–28	26–27	26–29	26–32
Site preparation	Manual	Mechanical	Mechanical	Mechanical
Planting month	Aug 2006	Oct 2001	Oct 2006	Aug 2006
Fertiliser	Once/year NPK	Twice/year NPK	Twice/year NPK	Twice/year NPK
Replicate	3	1	3	2
No. of trees per plot	49	67	49	100
Spacing (m)	4 × 4	3 × 3	3 × 3	3 × 3
Previous activity	Farm land	Poor lowland forest	Poor lowland forest	Lowland forest

Source: Suhaimi (2006); NPK = nitrogen, phosphorus, potassium

Methodology

The tree crown diameter measurement is based on the assumption by Krajicek et al. (1961) that the vertical projection of a tree crown is circular. Four radii measurements were taken in the direction forming equal angles. The average crown diameter (CD) was calculated by summing up the four radii and dividing by 2.

$$CD = \sum r_i / 2 \qquad (1)$$

where
$\quad$ CD = average crown diameter
$\quad$ r_i = projected crown radii measured on four
$\qquad$ axes

Diameter was measured for all tree individuals within the random sample of trees in the stands using a metal metric diameter tape graduated in centimetres.

Based on the calculated CD, the crown area (CA) was calculated (Krajicek et al. 1961) and expressed in ha.

$$CA = (3.1416 \times CD^2/10{,}000)\ /4 \qquad (2)$$

Analyses of data

Statistical analyses to determine the relationship between the response (crown diameter) and independent variables were analysed using SAS/STAT 1989 9.1 PROC REG procedure. The mean and standard error of the response variable were calculated using SAS/STAT 1989 PROC Summary.

Model testing

Six growth models were tested for best fit and magnitude of error associated with the regression.

$$\text{Model 1 } CD = a_0 + a_1\, dbh + a_2 dbh^2 + e \quad (3)$$

$$\text{Model 2 } CD = a_0 + a_1 \ln dbh + e \qquad (4)$$

$$\text{Model 3 } \ln CD = \ln a_0 + a_1 \ln dbh + e \quad (5)$$

$$\text{Model 4 } \log CD = a_0 + a_1 \log dbh + e \qquad (6)$$

$$\text{Model 5 } CD/dbh = a_0 + a_1(1/dbh) + e \quad (7)$$

$$\text{Model 6 } CD/dbh = a_0 + a_1(1/dbh) + a_2 dbh^2 + e$$
$$\qquad\qquad (8)$$

where CD = crown diameter (response variable); dbh (independent variable) = diameter at breast height; a_0, a_1 and a_2 = regression coefficients and e = error associated with regression.

The CD was fitted by the method of ordinary least square (OLS) (Vanclay 1994, West 1995). The OLS method assumed equal variance and unbiased estimates of the model parameters if observations were independent and had equal variances. However, in the prediction of CD, the adjustment proposed by Baskerville (1972) was applied if there was any indication of heteroscedasticity (heterogeneity of variance) with respect to diameter. If the assumption of homogeneity of variance was not met (increasing variation in residuals with increasing diameter), the response variable or CD was either transformed or weighted to alter the relationship between explanatory variables (Wan Razali 1988, Khali Aziz & Azmy 1994, Martin & Rafael 2004). The regression analyses were conducted as in models 1 and 2, which were untransformed, while transformed and weighted least squares were in models 3, 4, 5 and 6. In the weighted models, both sides of the model equation were divided by diameter as in equations 7 and 8.

Model transformation and comparison

Following transformation, the best model was selected based on the goodness of fit as indicated by r^2 (coefficient of determination), mean of the residuals (magnitude of errors associated with regressions) and root mean square error or standard error of fitted regression. The residual analyses were used to determine the lack of fit and biasness (West 1980, Wan Razali 1988). However, this method of selection seemed acceptable for simple models involving one or two functions (Alder 1995) and having same response or dependent variable (equations 3 and 4). Thus, the index of fit is the standard error of the regression. In contrast, transformed and weighted models (equations 5, 6, 7 and 8) were analysed using the Furnival index (Furnival 1961) as these models had different transformed and weighted response variables. The index adjusts the standard error of the regression in order to facilitate comparison. The Furnival index

(FI) was calculated by multiplying the standard error of the fitted regression with the geometric mean and the reciprocal of the derivative of transformed variable and weighted with respect to the untransformed variable.

RESULTS AND DISCUSSION

Table 2 shows the basic information obtained from the study plots and later used in the crown diameter prediction of plantation-grown *N. cadamba*. CD ranged from 3.0 to 14.8 m. In Sandakan, where the soil was more favourable, the average CD was 7.59 m. Figure 2 shows the relationship between measured CD and diameter at breast height (dbh) in each study site. Majority of the CD values were between 3.4 and 12.4 m in Sandakan and Sibu compared with Tawau and Setul from 3.8 to 14.8 m and 3.0 to 7.8 m respectively. Crown diameter increased with increasing tree diameter but leveled off after reaching diameter between 35 and 40 cm (Figure 2).

Using the OLS regression, the CD functions obtained were as follows:

Model 1 $CD = 3.3608 + 0.01127 (dbh) + 0.002735 (dbh^2)$ (9)
Root MSE 1.2089, $r^2 = 0.5543$

Model 2 $CD = -9.7317 + 6.5341 (\ln dbh)$
Root MSE 1.2757, $r^2 = 0.5013$ (10)

Model 3 $\ln CD = -0.259087 + 0.72141 (\ln dbh)$ (11)
Root MSE 0.16739, $r^2 = 0.4980$

Model 4 $\log CD = -0.11252 + 0.72141 (\log dbh)$ (12)
Root MSE 0.0727, $r^2 = 0.4980$

Model 5 $CD/dbh = 0.23653 + 2.03040 (1/dbh)$ (13)
Root MSE 0.05283, $r^2 = 0.1621$

Model 6 $CD/dbh = 0.20382 + 2.47061 (1/dbh) + 0.00002246 (dbh^2)$ (14)
Root MSE 0.05283, $r^2 = 0.1660$

Table 2   Stand and stock table of the four study sites

Site	Age	N	dbh (cm)	ht (m)	CD (m)	Range CD (m)
Setul	4	100	9.2	7.05	3.56	3.0–7.8
Sandakan	4	152	21.0	16.32	7.59	3.4–10.0
Tawau	10	120	24.3	21.76	4.61	3.8–14.8
Sibu	4	200	19.2	14.22	4.54	3.5–12.4

N = number of trees, dbh = average diameter at breast height, ht = average height, CD = crown diameter
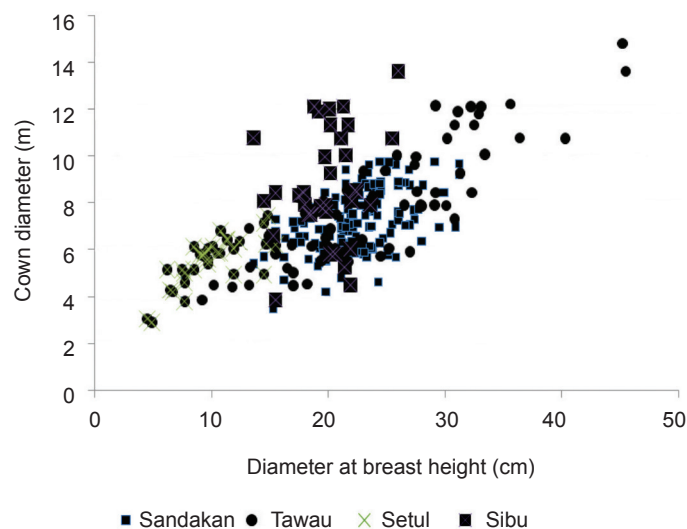

Figure 2   Distribution between crown diameter and diameter at breast height from different sites

Equations 9 to 13 show the results obtained from the OLS regression of the data from the study sites using six CD functions with different untransformed, transformed and weighted dependent variables. Based on these functions, models 2, 3, 4 and 5 conformed to *a priori* expectation of growth theory. However, for quadratic models 1 and 6 with dbh and dbh^2 as explanatory variables and with positive coefficient of dbh^2, the models predicted ever-increasing and unrealistic CD for large and larger trees, which was biologically untenable (Figure 3). The model may provide reliable prediction of periodic crown diameter growth over a limited range of diameter sizes up to 10 years, as extrapolation outside the range of independent variables is not acceptable in this study.

As pointed out by Dawkins (1963), the CD and dbh relationship should conform to Dawkins type 2 graph behaviour, i.e. positive intercept when CD/dbh ratio decreases with tree size (Table 3), implying that stand basal area increases towards maturity. As indicated in Figure 4, all models except 1 and 6 behaved accordingly, i.e.

decreasing CD/dbh ratio with tree diameter size. Models 1 and 6 predicted ever-increasing and unrealistic CD for large and larger trees, leaving models 2, 3, 4 and 5 as the preferred models (Figures 3 and 4).

Based on the above results, the preferred model was selected in accordance with the standard procedure: magnitude of standard error value for untransformed dependent variables against the value of FI for transformed and weighted dependent variables. As shown in Table 4, the model was selected by comparing the goodness of fit as measured by the highest r^2, lowest standard error of estimate of the fitted regression (Krajicek et al. 1961, Dawkins 1963) and lowest FI. However, this study comprised three different types of response variables. Thus, the best fit model for different dependent variables was selected using FI, in which the lowest index would be the preferred model. Model 5 had the lowest index and was, therefore, the preferred model with analysis of variance as in Table 5. The model explained the variation in CD with coefficient of determination (r^2) at 16.2%.
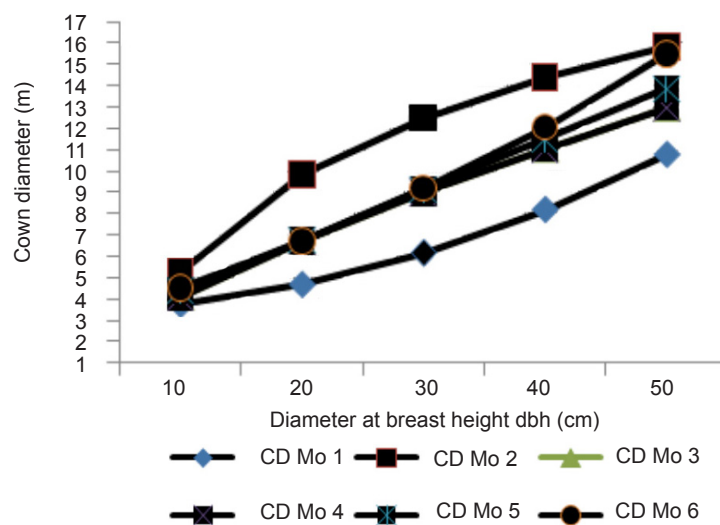

Figure 3   Graphical relationship between crown diameter and dbh for models (Mo) 1–6

Table 3   Values of CD/dbh ratios and dbh for models 1–6

dbh (cm)	CD/dbh1	CD/dbh2	CD/dbh3	CD/dbh4	CD/dbh5	CD/dbh6
10	0.375	0.533	0.406	0.406	0.439	0.453
20	0.234	0.493	0.335	0.335	0.338	0.336
30	0.205	0.417	0.299	0.299	0.304	0.306
40	0.205	0.360	0.276	0.276	0.287	0.301
50	0.215	0.317	0.260	0.259	0.277	0.309

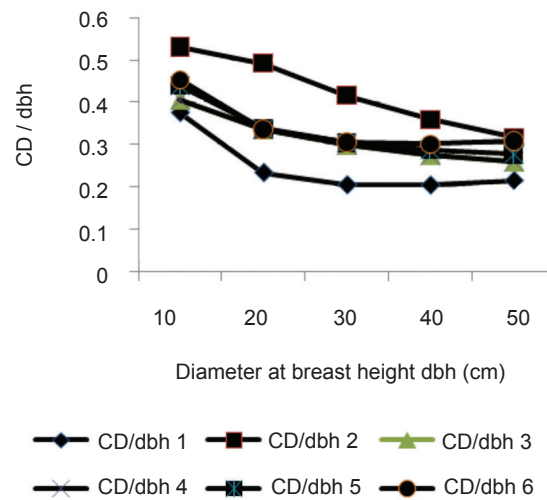CD = crown diameter, dbh = diameter at breast height

Figure 4   CD/dbh ratio and dbh relationship; CD = crown diameter

Table 4   The calculated standard error of fit, r^2 and values of Furnival index

Model	RMSE	r^2	FI
Model 1 CD = 3.3608 + 0.01127(dbh) + 0.002735 dbh^2	1.2089	0.5543	1.209
Model 2 CD = -9.7317 + 6.5341 (ln dbh)	1.2757	0.5013	1.276
Model 3 CD = e $^{(0.72141\ (\ln dbh)\ -0.259087)}$	0.1674	0.4980	0.330
Model 4 log CD = -0.11252+0.72141 (log dbh)	0.0727	0.4980	0.155
Model 5 CD/dbh = 0.23653 + 2.03040 (1/dbh)	0.0528	0.1621	0.017
Model 6 CD/dbh = 0.20382 + 2.47061 (1/dbh) + 0.00002246 (dbh^2)	0.0528	0.1660	0.017

CD = crown diameter, RMSE = root mean square error, r^2 = coefficient of determination, FI = Furnival index, e = 2.71818

The results were negatively biased as indicated by the positive mean residual (the difference between observed and predicted CD) of 1.33, a clear indication of underestimation by the models. For growth modelling studies, the ideal results should be unbiased or have zero mean residuals (Figure 5) with no consistent trends left unexplained for the dependent variables in the model (Alder 1995, West 1980).

The results obtained from the modelling works also provided means for computing the crown area (CA) of each tree expressed as a function of crown diameter.

$$CA = (3.1416 \times CD^2 / 10,000) / 4 \qquad (15)$$

$$CA = 3.1416 \times [(0.23653 + 2.03040\ (1/dbh)) *dbh]^2\ / 40,000 \qquad (16)$$

CA = crown area required by the tree, values 3.1416 and 40,000 = conversion of crown diameter in m to area in ha. Based on equation 16, trees having dbh of 30 cm would require a projected crown area of 0.0065 ha (65 m^2) for even-aged *N. cadamba* stands (Table 6).

Subsequently, the limiting stocking per hectare (N ha^{-1}) required for producing a complete canopy could be expressed as the inverse of crown area. From equation 16, the limiting stocking of the stand in terms of total occupancy by tree crowns could be determined. The stocking ha^{-1} (N) was 1/CA, i.e. 153 dominant trees of 30 cm dbh would fully occupy an area of 1 ha. Table 6 shows the estimated crown diameter, crown area and stoking per hectare of the species.

Besides generating knowledge on tree and crown sizes, the results obtained from this study explained the relation between CD and dbh. The information could assist managers in estimating the actual final crop and expected mean diameter at the end of a rotation period. The selected model might also be used in the estimation of an initial density during establishment. Overall, the results obtained helped in the current

Table 5   Results of the analysis of variance for model 5

Source	Df	Sum of square	Mean square	F value	Pr > F
Model	1	0.11016	0.11016	39.48	< 0.0001
Error	204	0.56929	0.00279		
Corrected total	205	0.67946			
		Root MSE	0.05283	r square	0.1621
		Dependent mean	0.32935	adj r-sq	0.1580
		Coeff var	16.03981		
Parameter estimate					
Variable	Df	Parameter estimate	Standard error	t value	Pr > |t|
Intercept	1	0.23653	0.01522	15.54	< 0.0001
Dbh	1	2.03040	0.32316	6.28	< 0.0001

Dependent variable: CD, dbh; CD = crown diameter, dbh = diameter at breast height; MSE = mean square error, coeff var = coefficient of variation
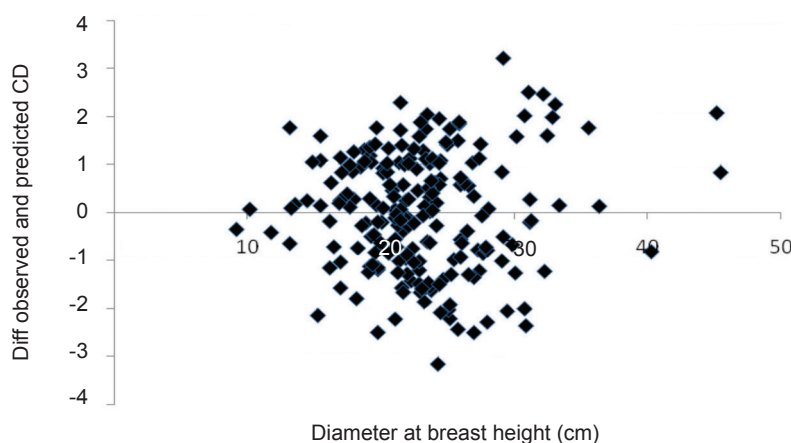Number of observations read = 206, number of observations used = 206

Figure 5   Residuals (the difference between observed and predicted values) with positive mean values of 1.33; CD = crown diameter; diff = difference

Table 6   The estimated crown diameter (CD), crown area (CA) and stocking (N ha^{-1}) from the modelling (model 5) of crown data of *Neolamarckia cadamba*

dbh (cm)	CA (ha)	Diff CA	CD (m)	Diff. CD	N ha^{-1}
10	0.0015	–	4.39	–	667
20	0.0036	0.0021	6.76	2.37	278
30	0.0065	0.0029	9.12	2.36	153
40	0.0104	0.0039	11.49	2.37	96
50	0.0151	0.0047	13.86	2.37	66

dbh = diameter at breast height; diff = difference

silviculture and management of the species under commercial forest plantation establishment.

CONCLUSIONS

Despite having underestimation results, the crown diameter prediction model using CD and tree diameter of planted *N. cadamba* helped in the determination and development of an appropriate management regime for the species. The relationship between CD and diameter might be useful in predicting crown area, number of potential final crop trees and future crown diameter.

ACKNOWLEDGEMENTS

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