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Relationships between Crown Size and Aboveground Biomass of Oil Palms: An Evaluation of Allometric Models

(Hubungan antara Saiz Silara Pokok dan Biojisim Atas Permukaan Tanah Kelapa Sawit: Penilaian Terhadap Model Alometri)

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ABSTRACT

Oil palms (OP) in Sabah, Malaysia were studied to explore the relationship between canopy size and aboveground biomass (AGB). Four available allometric equations were used to calculate the dry AGB. Pearson's correlation analysis was performed between crown diameter (CD) and crown area (CA) towards the variables of AGB, height and dbh. In this analysis, the transformation to natural log of variable resulted in better coefficient compared to the original one. The mean of various variables such as height (stem, total and height difference), biomass (crown, trunk and total), dbh (inner and outer) and number of petiole leaf were calculated based on 32 independent sample plots (N = 222 palms) across various age stages from 2 to 24 years. These variables were regressed against CD and age. AGB versus CD was a nonlinear with R^2 ranging from 0.950 to 0.975. Random modelling and cross validation between AGB and CD was applied at the ratio of 70:30. Upon checking, the best estimation was achieved by using the allometric equation based on total height due to the lowest relative root mean square error (RMSE) (18.5%) and the least fluctuation between predicted and actual AGB. The other three models had relative RMSE that ranged between 23.9 and 68.8%. This study shows that AGB can be estimated using CD of OP consistently at all ages.

Keywords: Aboveground biomass; allometric equation; crown diameter; oil palm

ABSTRAK

Kelapa sawit di Sabah, Malaysia telah dikaji untuk menentukan hubungan antara saiz kanopi pokok dan biojisim atas tanah (AGB). Empat persamaan alometri telah digunakan untuk mengira AGB kering. Analisis korelasi Pearson telah dijalankan antara diameter kanopi pokok (CD) dan luas kanopi pokok (CA) terhadap pemboleh ubah AGB, ketinggian dan diameter batang pada paras dada (dbh). Dalam analisis ini, penukaran kepada log asas bagi pemboleh ubah menghasilkan pekali yang lebih baik berbanding pemboleh ubah asal. Purata bagi pelbagai pemboleh ubah seperti ketinggian (tinggi batang, tinggi keseluruhan dan beza tinggi), biojisim (kanopi pokok, batang dan keseluruhan), dbh (dalam dan luar) dan bilangan pangkal daun telah dihitung berdasarkan 32 sampel plot yang tidak bersandar (N = 222 pokok sawit) merangkumi peringkat umur 2 hingga 24 tahun. Pemboleh ubah tersebut diregrasikan terhadap CD dan umur pokok. Perhubungan AGB menentang CD didapati tidak linear dengan R2 terjajar daripada 0.950 hingga 0.975. Pemodelan rawak dan validasi silang antara AGB dan CD telah dilakukan mengikut nisbah 70:30. Setelah diperiksa, penganggaran yang terbaik adalah menggunakan persamaan alometri ketinggian keseluruhan pokok berdasarkan hasil relatif sisihan purata punca kuasa dua (RMSE) (18.5%) yang terendah dan paling kurang sesaran antara AGB sebenar dan ramalan. Tiga model yang lain mempunyai relatif RMSE berjajar di antara 23.9 dan 68.8%. Kajian ini menunjukkan bahawa AGB boleh dianggarkan secara mampan pada semua peringkat umur menggunakan CD kelapa sawit.

Kata kunci: Biojisim atas permukaan tanah; diameter silara pokok; kelapa sawit; persamaan alometri

INTRODUCTION

Gazetted area for non-forest land use was extensively large in year 2010 in two countries known as major palm oil producers: Malaysia (12.40 million ha) and Indonesia (86.73 million ha) (Food and Agriculture Organisation 2010). Oil palm plantations dominate the non-forest land at 34.7% for Malaysia (Malaysian Palm Oil Board 2011) and 9.0% for Indonesia (Colchester et al. 2011). In Sabah alone, 20% of its current land area is OP plantations (Ancrenaz et al. 2013). Since the United Nations Framework Convention on Climate Change (UNFCC) requests for standard national reports on carbon emissions and stocks, the net aboveground biomass production of OP plantations must be quantified reliably and efficiently at frequent temporal resolution as a part of the monitoring effort. Thus, accurate biomass must be estimated for OP plantation. Biomass in OP plantation can be assessed based on the relationship between biomass and spectral radiance of OP (Thenkabail et al. 2004). However, OP's spectral radiance tends to saturate when the palm approaches maturity. Additionally, field measurement is simply too costly for extensive areas of OP plantations. In view of that, the satellite remote sensing approach is probably the best alternative to the field approach. This is because high resolution satellite imagery (HRSI), with a submeter resolution, enables the detection of individual oil palm crowns which store information that can be potentially useful to predict biomass. However, the relationships between OP crown variables and aboveground biomass have not been examined thoroughly (Roundtable on Sustainable Palm Oil 2012).

Morphologically, OP is a large, pinnate-leafed tree that has a solitary columnar stem with short internodes. The mature leaf is simply pinnate, bearing linear leaflets or pinnae on each side of the leaf stalk which later is divided into the rachis (bearing the leaflets) and petiole (shorter than the rachis and bearing only short lateral spines). OP biomass is divided into two major parts - the aboveground and belowground. The aboveground part consists of trunk and crown including the yield of fruit bunches, whereas the below ground part consists of only roots. The proportion of aboveground to belowground biomass for OP in Malaysia was estimated at 84.6% (± 4.2%) of the total biomass (Corley & Tinker 2003). Total height is the most common variable used to estimate the overall OP aboveground biomass (Khalid et al. 1999). Later, Corley and Tinker (2003) introduced an aboveground allometric equation that calculates biomass separately between fronds and trunk components. Age is also used in estimating the oil palm biomass (McMorrow 2001; Henson & Chang 2003). Estimation based on age results in average biomass which cannot account for biomass variations among same-age palms in a plantation. Apart from palm variety, site factors such as soil fertility level, topography and local climatic influences contribute to these variations.

On the other hand, crown variable has been proven useful in estimating forest biomass using medium- (Phua & Saito 2003) and high-resolution (Palace et al. 2008; Phua et al. 2014) satellite imageries. Crown diameter has been used to estimate biomass under the scenario of small sample size of field data (Phua & Saito 2003). Thus, in this paper, we examined the usefulness of OP crown variables in aboveground biomass (AGB) estimation. We evaluated the relationships of crown variables against AGB derived from four allometric models (Corle03, Thenk04, ICRAF09 and Khali99) that are widely used in OP AGB estimation. OP crowns and other structural variables at various age stages were measured in the field. Correlation regression analyses were carried out between crown variables and aboveground biomass.

MATERIALS AND METHODS

STUDY SITE

The present study was conducted in the district of Beluran in Sabah, Malaysia. The climate of the study area is equatorial with two monsoon rain seasons: from May to September and November to March. The mean annual temperature is 28°C, while annual rainfall is 3100 mm. The topography consists mainly of flat to undulating areas with an average elevation of 100 m above sea level. The field data for this study were collected at two sites - Sapi plantation and Sungai Ruku-Ruku plantation (Figure 1). The distance between these plantations is approximately 20 km.

FIELD DATA COLLECTION

At Sapi plantation, the age of palms ranged from 2 to 7 years whereas the palms at Sungai Ruku-Ruku plantation were between 11 and 24 years old. At an age of 24 years, a palm tree is considered old because the productivity is low and the fruits are laborious to harvest. Biomass accumulated in the trunk reaches the highest level at this phase. Nevertheless, a slight decrease in the accumulation rate is expected after the trees have reached 20 years old (Henson & Chang 2003). This may be due to the frond base decomposition and the slight shrinking of dbh. A total of 32 plots were established during five field trips from October 2011 to August 2012. Plots were determined on line transects in plantation blocks. Each plot was circular in shape with a radius of 15 m and consisted of 8-11 trees. Dbh, tree height (h), depth (d) and width (w) of leaf petiole, number of leaves per tree and crown diameter (CD) were measured for each palm. Outer dbh was measured at 1.3 m from the ground except for young palms with shorter trunk. Inner dbh was calculated by subtracting the outer dbh with an average dbh gap. Dbh gap measures the thickness of a frond base that is still attached to the trunk after pruning. However, ground observation found that dbh of OP trunk shrunk a little due to the decomposition of dead frond bases at the age of 18 years old and above. Height reading was taken using sonic-based Vertex unit at trunk and total height. For trees below 4 years old, dbh and height were measured at the base because there was no developed trunk. Average depth and width of leaf petiole were measured based on pruned leaf samples in every plot. Crown area and perimeter were calculated using sphere equation, $\pi(\text{CD})^2/4$ and $\pi(\text{CD})$, respectively. Crown was assumed a round shape.

In total, 222 individual palms at various age stages, which are young, early mature, mature, late mature and over mature stages, were measured in the field for statistical analysis (Table 1). For palms at a young age stage, 2-5 years old, they were measured every year as they tended to grow very fast at this stage. Meanwhile, for palms at other age stages, representative samples for each of the stages, at age 7, 15, 18 and 24 years were collected. This dataset was divided for modelling and cross validation with a ratio of 70:30.

ANALYSES ON RELATIONSHIP BETWEEN CROWN VARIABLES AND AGB

Four allometric equations were applied to calculate the AGB of palm trees (Table 2). The equation of Corley and Tinker (2003) uses dbh variable to calculate trunk biomass which

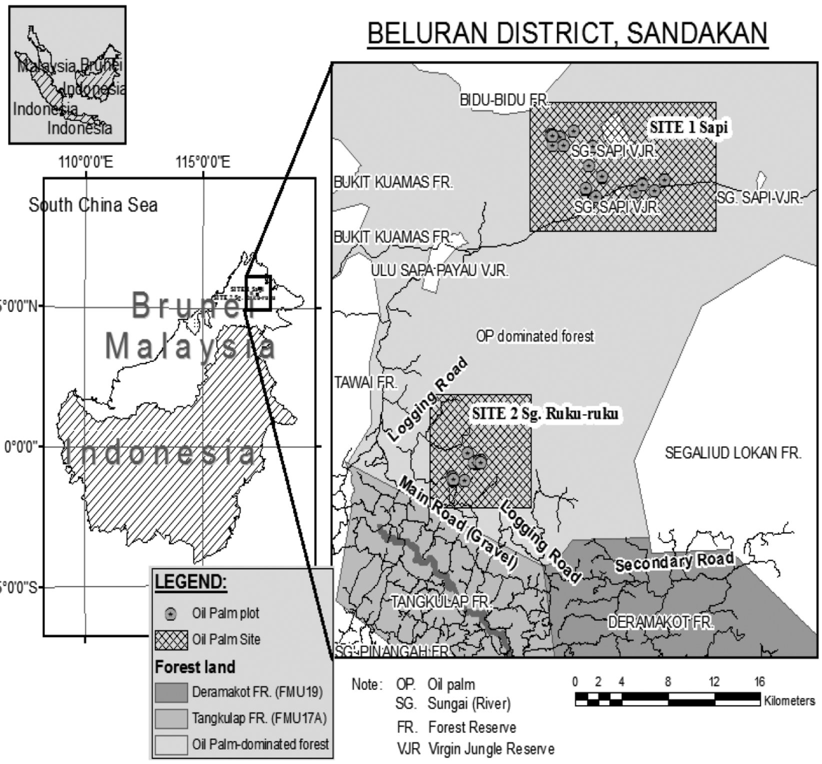

FIGURE 1. Study area consists of two sites - Site 1 (Sapi plantation) consisted of young age palm trees (from 2 until 7 years old) and Site 2 (Sungai Ruku-Ruku plantation) consisted of mature until over mature palm trees (from 11 until 25 years old)

TABLE 1. Data collection on oil palm plantation

Age (years)	Growth	Plot number	Date	Location
2	Young	4	Aug 2012	Site 1
*3		3 trees		(Sapi)
*4		36 trees		
5		4		
7	Early mature	4		
11 to 15	Mature	3	Jul 2012	Site 2
16 to 20	Late-mature	1	Feb 2012	(Sungai Ruku-Ruku)
24 to 25	Over-mature	16	Oct 2011 - Feb 2012	
TOTAL		36		

Note: * Based on individual selected sampling (equivalent to 4 plots)

is difficult to apply for palm trees with no significant dbh (below 3 years old). At this stage, the growth rate of palm trees are critically fast and the trunk only starts to form. Any calculation based on dbh needs detailed studies, which may result in specific transitional allometric equation. As such, equation that uses height to estimate biomass is more readily applicable.

Palm biomass, excluding fruit bunches, can be calculated for aboveground and total biomass in dry condition (Corley & Tinker 2003; Dewi et al. 2009; Khalid et al. 1999; Thenkabail et al. 2004). The allometric equation of Corley and Tinker (2003) depends on the tissue density of trunk to calculate biomass; greater age has a higher density. Using Corle03, biomass of fronds and trunks were calculated separately. The other three allometric equations use trunk and total height variables to estimate the standing biomass. Allometric equations of Dewi et al. (2009) and Khalid et al. (1999) calculate fresh biomass, but dry biomass can be obtained by multiplying with a constant of 0.2. Biomass of crown and trunk were calculated using the equation of Corley and Tinker (2003).

The strength of allometry relationships was investigated between crown variables (diameter, area and perimeter) and the other tree structural variables such as biomass (crown, trunk and total), height (trunk, total and height difference), dbh and number of frond (or leaf) per tree using Pearson's correlation analysis. The performance of crown width was also compared with age since age

TABLE 2. Allometric equations for OP aboveground biomass

Reference	Abbreviation	Type / Component	Equation	Estimator variable	Location of study
Khalid et al. (1999)	Khali99	Aboveground fresh weight (kg)	$\mathrm{AGB} = 725 + 197h_{\mathrm{total}}$	Total height	West Malaysia
Corley & Tinker (2003)	Corle03	Trunk density (kg/litre)	$\rho = 0.0076x + 0.083$	Total height, dbh, age, wood specific gravity, frond width and depth	World tropical region
		Dry weight trunk (kg)	$\mathrm{AGB}_{\mathrm{trunk}} = 0.1\pi\rho h_{\mathrm{total}}\left(\frac{\mathrm{dbh}}{2}\right)^2$		
		Dry weight frond (kg)	$\mathrm{AGB}_{\mathrm{frond}} = 0.02wd + 0.21$		
		Aboveground dry weight (kg)	$\mathrm{AGB} = \mathrm{AGB}_{\mathrm{trunk}} + \mathrm{AGB}_{\mathrm{frond}}$		
Thenkabail et al. (2004)	Thenk04	Aboveground dry weight (kg)	$\mathrm{AGB} = 0.3747h_{\mathrm{trunk}} + 3.6334$	Trunk height	West Africa
Dewi et al. (2009)	ICRAF09	Aboveground fresh weight (Mg)	$\mathrm{AGB} = 0.0976h_{\mathrm{total}} + 0.0706$	Total height	Sumatera and Kalimantan, Indonesia

where h_{total} is total height in m, h_{trunk} is trunk height in cm, dbh is trunk inner diameter in cm (trunk diameter measurement without frond bases), w and d is the width and depth of leaf petiole in mm, and x is age of OP in years.
Aboveground dry weight can be calculated from fresh weight biomass by multiplying with constant 0.2

was well known in estimating OP biomass. Natural log transformation variable was also performed for examining the relationships. Graphs were plotted to further explore crown diameter and age towards the mentioned tree structural variables. Crown based AGB estimation model was established and assessed based on regression model parameters and root mean square error (RMSE) of the estimation.

RESULTS

In this study, we examined the relationship of crown diameter (CD), crown perimeter (CP) and crown area (CA) against other variables: AGB (crown, trunk and total), heights (trunk and total), vertical crown depth, trunk dbh (inner and outer) and number of fronds. Results of Pearson correlation analysis between the crown and other variables are shown in Table 3. Since CP was derived from CD, only one of them was selected for regression analysis. There were strong correlations between CD and height and natural log of AGB (R: 0.769 ~ 0.900, $p = 0.01$). Original variables seemed to have lower coefficients (0.697 ~ 0.842, $p = 0.01$), compared to their corresponding transformed variables. CA possessed relatively weak correlation with the variables except for trunk height, crown biomass, trunk biomass and biomass difference. For OP crown, since large portion of biomass was stored in fronds (99.2%) compared to other crown's components such as spears and cabbage (0.8%) (Khalid et al. 1999), we then referred to the frond biomass as crown biomass. Dbh (inner and outer) and the number of fronds were not significantly correlated with CD or CA (R: -0.444 ~ 0.521). CD correlated better with natural log of AGB models (R: 0.888 ~ 0.899) compared to original AGB model (R: 0.758 ~ 0.842). For age, however, there were higher R coefficients for original AGB model (R: 0.925 ~ 0.928) compared to log transformed AGB model (R: 0.808 ~ 0.888) (Table 3).

Table 4 shows the structural characteristics and AGB of OP at different age stages. The structural variables and AGB were plotted against CD to examine the growth patterns (Figure 2(a)-2(g)). Estimated AGB and CD ratio with trunk height, crown depth and trunk dbh were also plotted against the corresponding age (Figure 2(h)-2(i)). All estimated AGB models had strong relationship with CD,

TABLE 3. Pearson's correlation analysis for linear relationships of crown width (diameter and area) and age with variables of AGB (crown, trunk, total and ΔAGB), height (total, trunk and Δheight), dbh (inner and outer) and N leaf (number of petiole leaf per tree) using 222 samples of data. Δheight is the height difference between total and trunk or also referred to as crown depth. ΔAGB is the biomass difference between trunk and crown component. Dbh is a diameter at breast height (about 1.3 m from ground). Performance of non-structural variable (age) is presented in the third column as comparisons for structural variable (crown width)

Variable	Crown diameter (Crown perimeter)	Crown area	Age
Ln(total height)	.900	.852	.853
Ln(Corle03)	.899	.855	.864
Ln(ICRAF09)	.898	.854	.864
Ln(Thenk04)	.889	.834	.808
Ln(Khali99)	.888	.855	.888
Ln(crown biomass)	.861	.822	.836
Ln(trunk biomass)	.848	.798	.821
Total height	.842	.837	.928
Khali99	.842	.837	.928
ICRAF09	.842	.837	.928
Trunk height	.806	.827	.959
Thenk04	.806	.827	.959
Ln(trunk height)	.804	.792	.826
Crown biomass	.782	.792	.885
Ln(Δheight)	.769	.674	.582
Corle03	.758	.781	.925
Trunk biomass	.735	.760	.908
Δheight	.721	.653	.617
ΔAGB	.697	.723	.877
Ln(inner dbh)	.521	.387	.187
Ln(outer dbh)	.471	.332	.122*
Inner dbh	.388	.247	-.020*
N_leaf	-.185	-.227	-.424
Outer dbh	-.390	-.444	-.681

All correlation was significant at the 0.01 level (2-tailed), except *.

TABLE 4. Mean values for crown width, height, AGB and dbh for respective age (N > 10 except for age 3 and 18) in 32 plots (2.26 ha) using 222 samples. Number of frond per tree is also included in last row. Ratio with CD is a ratio of other tree structural variables with crown diameter

		Average value (± S.E.) [min, max]							
		Young				Early Mature	Mature	Late mature	Over mature
	Age (years)	2	3	4	5	7	15	18	24
	Number of sample, N	10	3	33	38	38	32	9	59
	CROWN VARIABLE								
	Diameter/Perimeter	3.6	3.8	7.3	8.8	9.3	10.3	10.9	11.8
	(m)	(0.4)	(0.3)	(0.9)	(0.7)	(0.8)	(1.0)	(1.0)	(1.3)
		[3.1, 4.2]	[3.6, 4.2]	[5.9, 8.8]	[7.6, 10.3]	[7.9, 10.9]	[8.5, 11.9]	[9.4, 12.1]	[9.1, 15.5]
	Area (m^2)	10.3	11.6	42.6	61.7	67.9	83.5	93.6	110.6
		(2.1)	(1.8)	(10.9)	(9.1)	(12.5)	(15.3)	(16.0)	(25.1)
		[7.3, 13.5]	[9.9, 13.5]	[27.3, 60.1]	[45.4, 82.5]	[49.0, 93.3]	[56.1, 111.2]	[69.4, 114.0]	[64.3, 187.5]
	Independent variables								
Total AGB	Thenk04	0.093	0.117	0.215	0.319	0.406	0.578	0.698	0.736
	(Mg)	(0.02)	(0.02)	(0.03)	(0.04)	(0.04)	(0.08)	(0.06)	(0.09)
	Corle03	0.010	0.034	0.057	0.128	0.212	0.458	0.803	0.768
	(Mg)	(0.00)	(0.01)	(0.02)	(0.03)	(0.05)	(0.16)	(0.09)	(0.17)
	ICRAF09	0.067	0.079	0.130	0.185	0.230	0.319	0.382	0.402
	(Mg)	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)	(0.04)	(0.03)	(0.05)
	Khali99	0.251	0.276	0.380	0.490	0.581	0.761	0.887	0.928
	(Mg)	(0.02)	(0.02)	(0.03)	(0.04)	(0.04)	(0.08)	(0.07)	(0.10)
Component AGB	Crown biomass	10.0	31.2	41.0	43.7	59.0	104.8	139.4	132.6
	(kg)	(1.9)	(6.1)	(7.6)	(7.6)	(24.9)	(15.3)	(28.9)	(27.2)
	Trunk biomass	NA	3.2	16.1	84.5	152.5	353.1	663.9	635.1
	(kg)		(2.0)	(10.1)	(22.6)	(44.0)	(156.9)	(100.4)	(165.1)
	Biomass	-10.0	-28.0	-24.9	40.9	93.5	248.3	524.5	502.5
	difference (kg)	(1.9)	(6.4)	(9.5)	(20.0)	(55.1)	(150.7)	(114.7)	(167.6)
Height	Total height	2.7	3.3	6.0	8.7	11.1	15.6	18.8	19.9
	(m)	(0.4)	(0.4)	(0.9)	(1.0)	(1.1)	(2.1)	(1.7)	(2.5)
	Trunk height	NA	0.2	0.5	2.4	3.8	7.8	10.4	11.7
	(m)		(0.1)	(0.2)	(0.5)	(0.5)	(1.4)	(0.8)	(1.8)
	Crown depth	2.7	3.1	5.5	6.4	7.2	7.9	8.4	8.2
	(m)	(0.4)	(0.4)	(0.8)	(0.7)	(0.9)	(1.3)	(1.3)	(1.6)
Trunk diameter	Inner dbh	NA	42.3	58.4	61.0	60.3	53.0	60.6	50.8
	(cm)		(4.4)	(6.4)	(3.7)	(6.4)	(7.9)	(3.8)	(6.1)
	Outer dbh	NA	55.0	76.8	79.2	79.1	67.8	78.7	56.9
	(cm)		(4.0)	(6.8)	(4.7)	(9.0)	(8.9)	(5.0)	(9.4)
Ratio with CD	Trunk height	0.00	0.05	0.07	0.27	0.42	0.76	0.97	1.00
	Total height	0.75	0.87	0.82	0.99	1.20	1.53	1.74	1.70
	Crown depth	0.75	0.82	0.75	0.72	0.78	0.77	0.78	0.70
	Dbh	0.00	11.01	8.05	6.91	6.55	5.17	5.61	4.37
	Number of fronds	28.1	34.0	47.8	39.4	38.0	25.8	34.3	32.7
		(3.2)	(2.6)	(9.0)	(3.9)	(5.9)	(3.8)	(7.1)	(6.7)

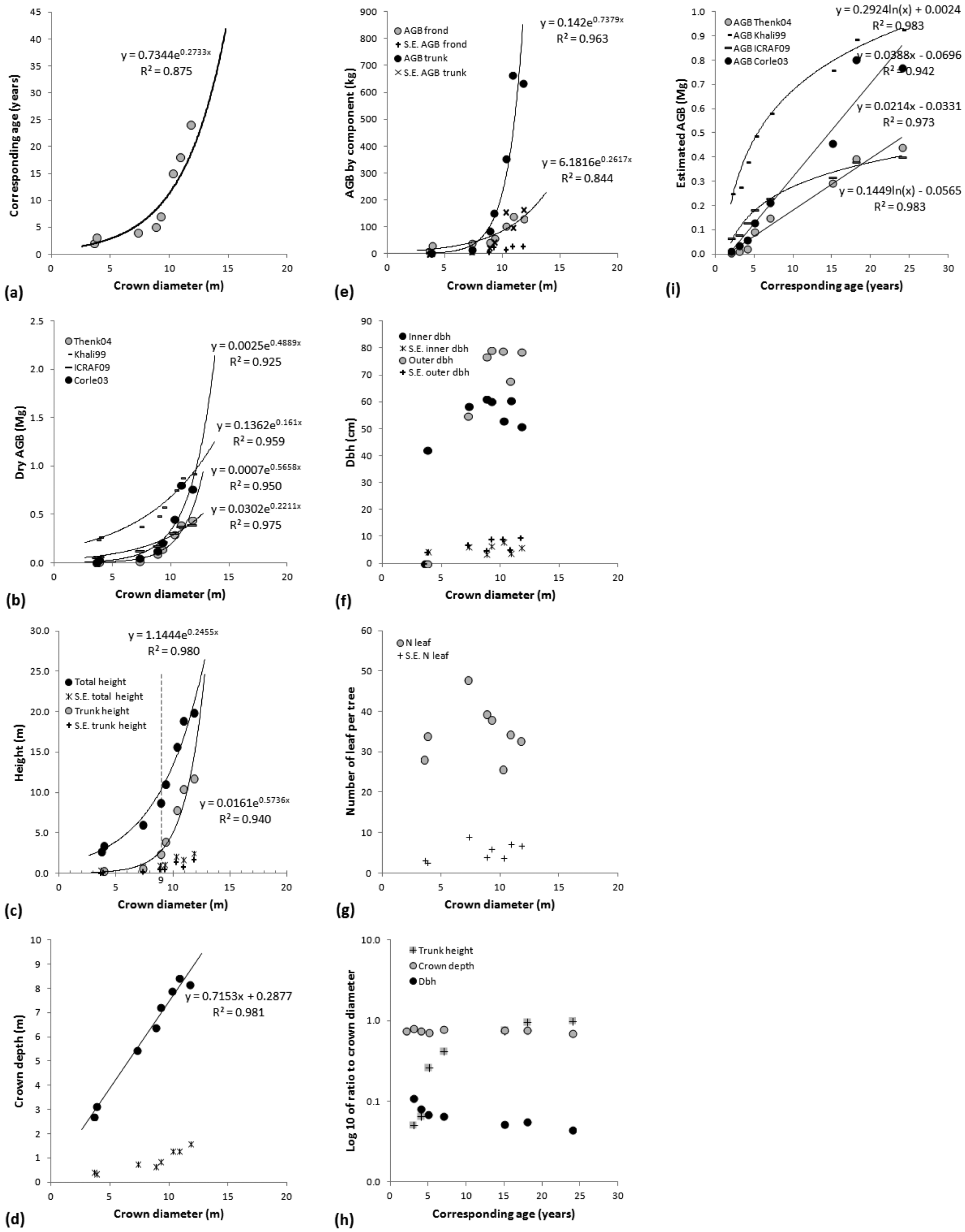

FIGURE 2. Overall changes in various variables such as age (a), AGB (b and e), tree height (c), crown depth (d), dbh (f) and N leaf (g) with increasing crown diameter for oil palms. Data was pooled according to age. Most relationships were nonlinear, except for crown diameter vs. crown depth (linear), whereas variable dbh and number of leaf per tree had no significant relationship with crown diameter. Changing pattern of estimated AGB and ratio to crown diameter for variables trunk height, crown depth and dbh over ages are also presented (h - i)

R^2 above 0.9 (Figure 2(b)). Both total and trunk heights were also strongly related with CD, R^2 of 0.98 and 0.94, respectively. However, the standard error (S.E.) for height (both trunk and total) seemed to increase when palms got taller (Figure 2(c)). Trunk biomass fluctuated less (R^2 = 0.963) compared to crown biomass (R^2 = 0.844) (Figure 2(e)). Trunk biomass accumulated rapidly from young until it reached the over mature phase (maximum was 663 kg, ± S.E. 100 kg), whereas crown biomass showed lesser increment (maximum was 139 kg, ± S.E. 28 kg). The standard errors of biomass in crown and trunk components were expectedly varied at 15-20%. The fluctuation of crown biomass depended on the number of fronds on a tree, which was highly subjected to leaf production and abscission activities (annual pruning and cutting during harvesting). It is noticed that the differences between trunk and crown biomass (Table 4) had increased and shifted from the negative to positive values at an age of 4 or 5 years. This indicates that the biomass storage in fronds was overtaken by the trunk (Figure 2(e)). It was also an indication that OP started to produce fruit bunches.

There was no significant relationship between CD and dbh (inner and outer) and the number of fronds (Figure 2(f) and 2(g)). Crown size was about the same across all age stages, as illustrated by a relatively flat pattern of crown depth and CD (Figure 2(h)). The relationship between crown depth and CD was linear with R^2 equal to 0.981 (strong relationship) (Figure 2(d)). Trunk OP grew taller but dbh did not proportionally become larger as commonly observed in the growth of forest tree due to very little or no secondary thickening growth in the stems of the palm trees (Corley & Thinker 2003). This argument was supported by the performance ratio between dbh to CD over years which slightly decreased during the young age-stage and then a flat when it reached the mature phase (Figure 2(h)). Meanwhile, the ratio between trunk heights and CD increased rapidly during the young age-stage but it decreased when it reached the mature phase. In general, AGB increased with age by different mixed functions. However, all regression models R^2 were larger than 0.9 (Figure 2(i)). Corle03 and Thenk04 were linear, whereas ICRAF09 and Khali99 had logarithmic functions. All four models increased exponentially with CD (Figure 2(b)).

Table 5 shows the results of linear regression analyses of CD against natural log AGB, from four estimation models (Thenk04, ICRAF09, Khali99 and Corle03), using 156 palms from young to over mature stages. Adjusted R^2 of the models ranged between 0.786 and 0.811 and the standard error ranged between 0.185 and 0.529. This indicates that linear model was a good fit between CD and AGB. Average OP AGB per life time and relative RMSE of the estimated AGB were also calculated for each model, using the remaining cross-validation dataset of 66 samples. At average, OP tree stored 0.223 to 1.311 Mg in one life cycle. The relative RMSE ranged between 18.5 and 68.8%. Among the four allometric equations, allometry equation of Khali99 was best used with CD because of the lowest standard error and relative RMSE. The adjusted R^2 for Khali99 model was the lowest and also most consistent among the four. Even though Corle03 model had the highest adjusted R^2 but its standard error was also high. This led to a high relative RMSE (68.7%). Corle03 and Thenk04 had high relative RMSE due to crown biomass fluctuation. Among the four models, Khali99 produced the highest average biomass stored per life time.

Figure 3 shows the fluctuations in estimated AGB of palms of the same age using different allometric equations. On the left, the estimated biomass was plotted against actual biomass using the validation samples (N = 66). On the right, actual AGB was compared with estimated AGB in a bar graph to show the consistencies of variation across all ages. Overall, AGBs were underestimated at 0.88, 1.92 and 16.56% for Khali99, ICRAF09 and Corle03, respectively. Only Thenk04 overestimated AGB for 1.85%. The estimated AGB using Khali99 and ICRAF09 showed a good fit with the actual AGB (R^2: 0.639 and 0.646) compared to using Corle03 and Thenk04 (R^2: 0.393 and 0.534). Crown based AGB estimation using Khali99 and ICRAF09 showed a consistent estimation compared to using Corle03 and Thenk04. AGB estimated using Thenk04 and Corle03 were adversely affected by separate AGB calculations between OP components in the allometric equations. AGB fluctuation amongst OP of the same age indicates different growth rates for each palm.

DISCUSSION

Currently, height has been used to estimate AGB in OP plantation (Corley & Tinker 2003; Dewi et al. 2009; Khalid et al. 1999; Thenkabail et al. 2004). In tropical forest, dbh has been used to estimate AGB (Basuki et al. 2009; Kenzo et al. 2009; Yamakura et al. 1986). Apart from that, the relationship of CD and forest AGB has also been examined and used as an alternative method in AGB estimation (Osunkoya et al. 2007; Palace et al. 2008; Phua & Saito 2003). In this study, the suitability of CD as an estimator of OP AGB was examined. Apart from the correlations between CD and other structural variables (crown depth, dbh and height), non-structural variable (age) was also explored. Most of the correlations were nonlinear. This complies with the nonlinear growth pattern of OP as well as its fruit production (Henson 1999; Khamis et al. 2005). The relationship between CD and age was exponential (Figure 2(a)) – fast increment during the early phase of planting but it became slower when CD was 9 m. The age estimated using CD in this study was 62% accurate compared to 75% in Thenkabail et al. (2004), which had used four multispectral bands of IKONOS. On the other hand, trunk height seemed to increase at a faster rate when CD reached 9 m. Meanwhile, CD was just about the same measurement with crown depth during its growth from young to over mature age-stage (Figure 2(h)). OP adapted by changing from crown expansion to trunk height elongation to search for maximum sunlight for photosynthesis. As a result, more aboveground

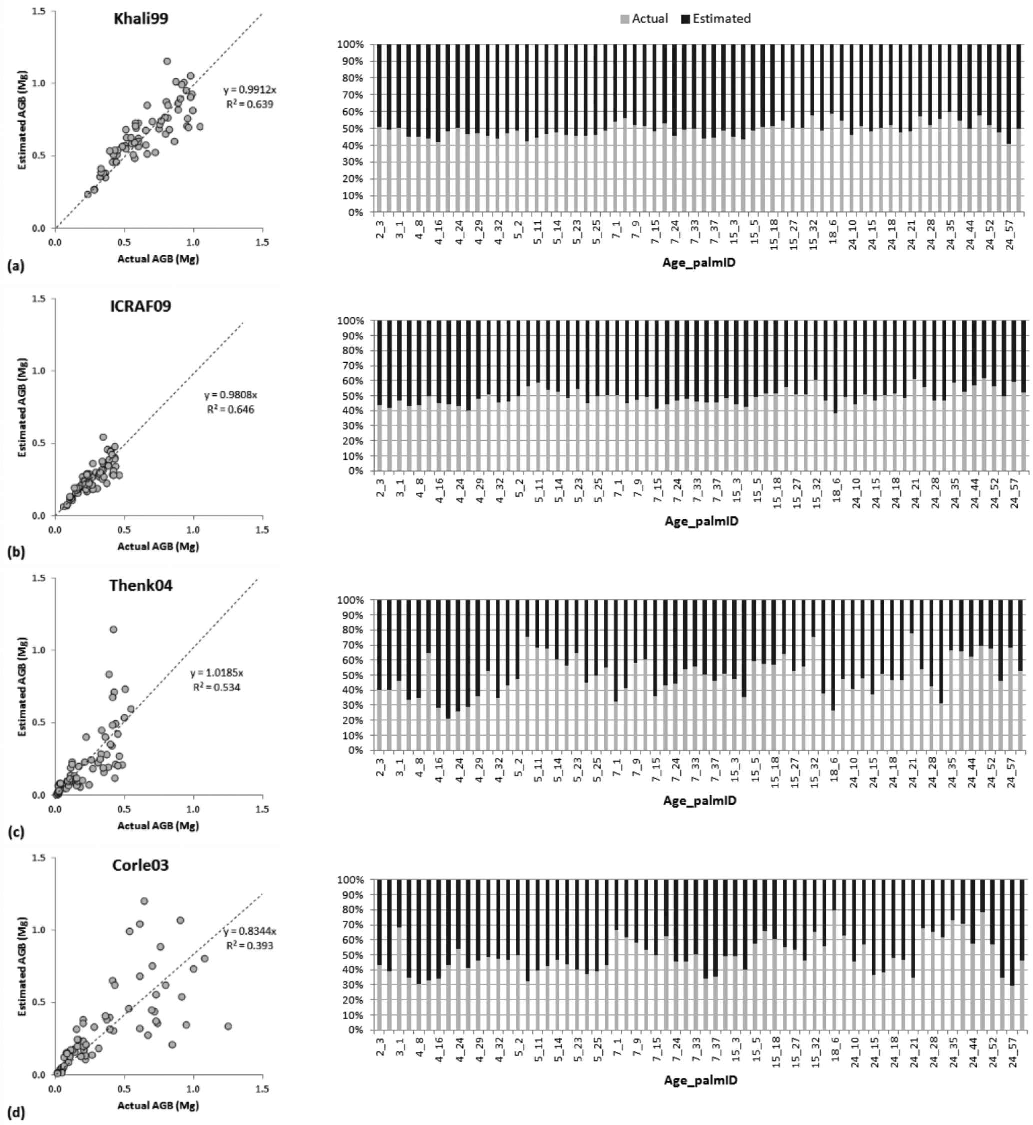

FIGURE 3. Performance of AGB estimation model (a-d) using crown diameter (CD) as estimator. AGB was estimated using the regression models in Table 5. A total of 66 random samples were used. Scatter plots between the estimated and actual value of AGB are presented on the left. Bar graphs show the intra-age and inter-age fluctuations of estimated AGB from young to over-mature stage

biomass was stored in the trunk compared to the crown. Excessive pruning could also have caused OP to grow higher because of the rapid emerging of new fronds. Khalid et al. (1999) reported that the percentages of AGB in over mature OP (23 years old) were 48% in trunk, 21% in frond bases, 28% in fronds (leaflets and rachises) and 3% in miscellaneous parts (spears, cabbage and inflorescences) or equivalent to 0.63 Mg per palm. The trunk biomass was 2.4 times higher than the fronds. In our study, we found that AGB was 0.93 Mg per palm and the ratio of trunk-to-frond biomass were 0.9, 3.4 and 4.8 for palms at the young, mature and over-mature stages, respectively (Table 4; Figure 2(e)). It was also found that OP biomass in Beluran, Sabah was higher than those in West Malaysia, based on studies conducted in Kluang, Johor (Khalid et al. 1999) and Perak (Shashikant et al. 2012). Structurally, the height of over mature OP (19.9 ± 2.5 m) in this study was 2.6 times higher than those in Kluang, Johor (7.48 ± 0.6 m). This significant difference may be due to factors such as soil fertility, climate variation, topographical condition, clone variety or the management aspect which were not relevant in the context of this study. This study mainly focussed on exploring the relations between AGB and structural variables. Based on trunk-to-frond biomass ratio, it is evident that AGB of young OP was mainly stored in the crown component before it was overtaken by the trunk when the OP became older. Fluctuation in crown biomass was expected to occur for active OP, which was caused by frond removal either due to annual pruning or removal during harvesting (24 fronds per year). New fronds emerged to replenish the crown biomass. Chan (1999) reported that the average

TABLE 5. Crown based AGB linear estimation model developed using 156 samples of palms covering stages of young (2, 3, 4 and 5 years), early mature (7 years), mature (15 years), late mature (18 years) and over mature (24 years) oil palms. Mean and RMSE were calculated using 66 samples which were randomly selected

Independent Variable			Dependent Variable			
			Thenk04	ICRAF09	Khali99	Corle03
			Natural log of AGB			
Crown diameter	Model summary	Adjusted R^2	0.788	0.804	0.786	0.811
	(sig. < 0.01)	S.E.	0.632	0.231	0.185	0.529
	Parameter Estimates	Estimator coefficient	0.519	0.199	0.151	0.466
		(± S.E.)	(0.022)	(0.008)	(0.006)	(0.018)
		Constant	-6.974	-3.326	-1.923	-5.921
		(± S.E.)	(0.209)	(0.077)	(0.061)	(0.175)
			AGB			
		Mean (Mg/individual)	0.223	0.262	0.646	0.380
		Relative RMSE	68.8%	23.7%	18.5%	68.7%

crown biomass throughout the age stages was 115 kg, comparable with the crown biomass of 15 years old OP (105 kg) in this study. Meanwhile, the trunk continued to grow higher and accumulated biomass until 635 kg.

AGB fluctuation can also be due to intra-competition for sunlight, nutrients and water among OPs. This was shown in the different growth rates between OPs planted at the same time. Topographically, OPs in the valley, which were more fertile, may grow faster than those planted at hill slope areas. In a tropical forest, understory trees tend to have increased crown size to capture the very limited amount of sunlight (Osunkoya et al. 2007). The correlation between CD and trunk height provides the basis to establish a model to estimate OP AGB. Khali99 allometry was the best because the relative RMSE was the lowest among the four tested allometries (Table 5). Besides, the percentage of the estimated AGB did not fluctuate much from the actual AGB compared to other allometries. The allometry of Khalid et al. (1999) uses all components of OP such as trunk, leaflets, rachises, spears, cabbage, frond bases and inflorescences (except fruit bunches) in the allometric equation. Other allometries such as Thenk04, ICRAF09 and Corle03 estimated lower mean AGB compared to Khali99 (-34.4, -40.6 and -58.8%, respectively). AGB estimated with allometries of Corle03 and Thenk04 at 5.3 and 3.0 Mg ha^{-1} per year. This is within the range of published AGB such as 5.0 Mg ha^{-1} per year (Dewi et al. 2009).

CONCLUSION

OP AGB has significant relationships with structural variables. We examined the relations between CD and AGB, as well as non-structural (age) and structural (height, crown depth, dbh) tree variables. We compared the suitability of each allometric equation used in OP plantation to calculate AGB. Our findings conclude that Khali99 is the best performed allometry for AGB estimation using CD. Since CD can be quantified using aerial photos and high resolution satellite image, therefore, it is potentially useful for monitoring OP AGB at a relatively large spatial scale.

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