Allometric Model for Predicting Aboveground Biomass and Carbon Stock of *Acacia* Plantations in Sarawak, Malaysia

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Allometric equations estimating biomass and carbon stock for *Acacia mangium* in Malaysia have been developed. However, in previous studies they were obtained from small trials or experimental plots. In this study, models were proposed to quantify the aboveground biomass as well as the amounts of stored and sequestered carbon in two planting variants, namely second generation *Acacia mangium* and *Acacia* hybrid plantations that were approximately 10 years old. Linear, power, exponential, and logarithmic functions were fitted for aboveground biomass using trunk diameter at breast height (DBH) as the independent variable. The best fit model for estimation of total aboveground biomass was in the form of a power function $y = aD^b$. Application of the developed model yielded total aboveground biomasses of *Acacia* hybrid and second generation *Acacia mangium* of 113.3 Mha^{-1} and 178.9 Mha^{-1}, respectively. This study indicated that 10-year-old second generation *Acacia mangium* and *Acacia* hybrid had sequestered 30.8 Mha^{-1} and 19.5 Mha^{-1}, respectively, of CO_2 annually. This study showed that the *Acacia mangium* plantation plays a role as a carbon sink. Thus, these forest plantations benefit the economy and also mitigate carbon emissions.

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INTRODUCTION

In Sarawak, Malaysia, *Acacia mangium* is the major species used in the establishment of planted forests. As of December 2017, Sarawak had established a total of 408,738 ha of forest plantations, of which 64% are planted with *A. mangium*. Other species planted include *Paraserianthes falcataria* (15%), *Eucalyptus* spp. (11%), *Neolamarckia cadamba* (6%), and others, such as *Swietenia macrophylla*, *Gmelina arborea*, and *Durio zibenthinus*, which make up the final 4% (Forest Department Sarawak 2018). *Acacia mangium* comes from the Leguminous/Fabaceae family, which is planted primarily for timber wood and firewood purposes (Arentz 1995; Sien and Mitlöhner 2011). In addition, forest plantations can play an important role in ecosystem rehabilitation. The role that fast growing plantations can play in carbon sequestration is gaining recognition (Samson *et al*. 1999; Paquette and Messier 2010; Ming *et al*. 2014) and *A. mangium* plantations have been considered a Clean Development Mechanism (CDM) for climate change mitigation (Morikawa *et al*. 2002; Matsumura 2011). In this era of carbon accounting and trading, measurements of carbon stock and sequestration of forest plantations are essential. Since *A. mangium* is the most popular choice for forest plantations in Sarawak the determination of its potential to store and sequester carbon is important.

Recently, two improved planting materials (hereafter referred to as "variant") have been introduced in Sarawak: second generation *Acacia mangium* and *Acacia* hybrid. Second generation *Acacia mangium* is actually *Acacia mangium* produced through artificial selection of seeds obtained from best phenotypes. Alternatively, natural hybridization of *Acacia mangium* and *Acacia auriculiformis* produced the *Acacia* hybrid. They are known to grow better and have more resistance to pests and diseases, as they were bred to have these desired traits from their parental species (Jusoh *et al*. 2014). The characteristics that they have are quite promising and beneficial to not only wood-based industries but also to those contributing to the mitigation of issues of abundance of greenhouse gases *via* carbon sequestration and carbon storage. Because trees can store large amounts of carbon in their biomass, there is also considerable potential for *A. mangium*, as long as the wood is used for making products in which it constitutes an additional carbon stock value. The potential of forest plantation in carbon sequestration requires reliable sources of carbon stock and biomass density estimates (Brown 1997; Kenzo *et al*. 2009a).

The estimation of carbon sink or sequestration relies on biomass content and growth data. Biomass content can be measured by direct or indirect methods (Bonham 2013). Direct methods consist of felling trees, cutting them into sections, and weighing them to obtain the actual biomass. Indirect methods are based on developed equations to estimate tree biomass. The carbon absorbed in plants can be estimated by using diameter at breast height (DBH) and height as predictors. There are many equations for estimating biomass, and previous researchers have reported that the allometric equation for a forest must be selected appropriately in order to accurately estimate forest biomass because these equations differ significantly between forest types (Pinard and Cropper 2000; Cairns *et al*. 2003; Hashimoto *et al*. 2004; Jepsen 2006; Kenzo *et al*. 2009a).

Several biomass estimates regarding *A. mangium* plantations in particular have been made by many researchers (Halenda 1989; Tanouchi *et al*. 1994; Hardiyanto *et al*. 1999; Morikawa *et al*. 2001; Diana *et al*. 2002; Morikawa *et al*. 2002; Heriansyah *et al*. 2003). A general equation for estimating biomass in *A. mangium* plantations was suggested by Hiratsuka *et al*. (2003). By using data from four plantations in Madang (Papua New Guinea), Sonbe (Vietnam), Banakat (Indonesia), and Bogor (Indonesia), the aboveground biomass (AGB) allometric equation they developed was $0.1876D^{1.131}$ with $R^2 = 0.95$ using diameter at breast height (D) as the independent variable. Another biomass estimation equation proposed by Banaticla *et al*. (2005) was $0.342D^{2.073}$ in which D as diameter at breast height. This particular equation was developed using secondary data of plantations in various sites in the Philippines.

Although estimations of *A. mangium* in Malaysia has been reported, they are not only obsolete, but also they were obtained from small trials or experimental plots. The derived equations from these plots may not accurately reflect biomass in commercial plantations. Moreover, biomass and carbon content values vary with age, tree species, site condition, growth rate, and silvicultural treatments applied in the stand (Brown 1997; Alexandrov 2007; Heriansyah *et al*. 2007). The relationship between biomass and tree variables is influenced by geographic location, land cover, and management practices (de Gier 2003). For these reasons, it is recommended that species and site specific equations be developed and used whenever possible (Banaticla *et al*. 2005). This study emphasized the estimation of AGB and carbon stock of second generation *A. mangium* and *Acacia* hybrid planted in Sarawak. The specific objective of this study was to develop allometric models to estimate the AGB of second generation *A. mangium* and *Acacia* hybrid trees.

The models were then used to determine the amount of carbon stored and sequestered by these two *Acacia* variants in a plantation setting.

EXPERIMENTAL

Study Area

The study site was located in an *A. mangium* plantation owned by Daiken Sarawak Sdn Bhd (03°21.347' N and 113°27.129' E) in Bintulu district, Sarawak. As of July 2015, the total planted area was 4500 ha, in which the bulk (85%) of the area was planted with second generation *A. mangium*. The soils are well-drained, fine, and loamy, and belong to the family of red-yellow podzolic soil of the Bekenu series (Tie 1982). Average annual rainfall in 2014 was 3,631 mm, and temperatures ranged from 23 °C to 33 °C (DID 2015). The area was previously a shifting cultivation area, and the status of the soil was considered to be that of low fertility (Paramanathan 2000). The climate is influenced by the monsoon, the northeast monsoon season from November to March and the southeast monsoon season from May to September. The area is flat to undulating, but with a slope of less than 15%. The areas which were planted from 2002 to 2004 had mostly been harvested and was then undergoing second cycle planting. Although small scale shifting cultivation is still taking place, the surrounding areas are dominated by oil palm plantations.

Field Sampling

Field sampling was conducted from June 2011 to September 2012. The plantation consists of even-aged stands, and the oldest stand was about 12 years old. Two 10-year-old stands, both from second generation *A. mangium* and *Acacia* hybrid, were selected. Five sampling plots of 30 m x 30 m each were established randomly in each of the two stands. The direct method was employed to determine the biomass of each tree. Thirty five trees of second generation *A. mangium* and 36 trees of *Acacia* hybrid were harvested from the sampling plots within the two stands. Trees were felled close to ground level. The trees were selected to ensure a representative distribution of diameter classes within the sampling plots. The DBH of the trees was measured to the nearest 0.1 cm before felling. Tree DBH is defined as outside bark diameter at breast height (1.3 m above the forest floor) on the uphill side of the tree. Following felling, the total tree height and merchantable height of each tree was measured to the nearest 0.01 m. Total tree height measured was according to its definition, the vertical distance from the base of the tree to its uppermost point (the tip of the tree). Merchantable length was taken from the ground level to the length where tree diameter tapers to 10 cm.

Determination of Green and Dry Weight

The plant components such as leaves, branches, and stems, of the felled trees were divided. It was impractical to separate the leaves from the twigs; instead, all twigs with leaves were weighed in bulk. Subsequently, representative subsamples of twigs were defoliated, and the twigs and leaves were weighed separately. To facilitate weighing, all stems were further cross-cut to a bolt length of one meter and all bolts were weighed. Following weighing, a wood disc approximately 2.5 cm thick was cut from each bolt and served as representative subsample of the bolts. Upper stems with a diameter less than 10

cm was taken as a branch. All twigs and other branchlets were included as branches. Green weight, also known as fresh weight, of all the components was recorded on field immediately after the trees were harvested.

The representative subsamples of twigs, leaves, branches, and stems (discs) from each tree were taken to the laboratory to be oven-dried. Prior to oven drying, all the samples were left to dry at room temperature for about eight weeks. Oven drying of stems and branches was done at 105 °C while twigs and leaves were dried at 80 °C until they reached their constant dry weight. This drying process usually took 10 days to 15 days. The total dry weight of each component was determined from the ratio of dry-weight to fresh weight of the corresponding subsamples. The total AGB was obtained by summing the stem, branches, and leaves biomass.

Development of Biomass Allometric Model

Biomass equations using DBH as the independent variable were developed and were regressed against the total AGB of the combined tree components (leaves, branches and stems). Total AGB allometric model of individual trees were derived from 35 and 36 trees for second generation *A. mangium* and *Acacia* hybrids, respectively. Four forms of the model, namely linear (Eq. 1), power (Eq. 2), exponential (Eq. 3), and logarithmic (Eq. 4), were fitted for total AGB. The following models were considered for estimating AGB (y, kg dry weight) from DBH (D), where a and b are coefficients:

$$y = aD + b \tag{1}$$

$$y = aD^b \tag{2}$$

$$y = ae^{bD} \tag{3}$$

$$y = a\ln(D) - b \tag{4}$$

Equations 1 and 2 are commonly developed from AGB studies (Brown 1977; Clough and Scott 1989; Hiratsuka *et al*. 2003; Banaticla *et al*. 2005; Kenzo *et al*. 2009b; Xue *et al*. 2012). Previously, Marklund (1987) and Muukkonen (2007) developed exponential biomass equations for some tree species in Europe. A logarithmic equation was developed for estimation of AGB in a lowland dipterocarp forest (Basuki *et al*. 2009). Curve fittings were performed using SPSS version 24 (IBM Corp., New York, USA 2016)

Model Selection

Model comparisons were done to determine which of the regressed equations best fit the data. Instead of primarily using the coefficient of determination (R^2), residual sum of squares (RSS) and Akanke Information Criterion (AIC) were employed for model comparisons and selection for best fit. Model comparisons using only the coefficient of determination (R^2) can present misleading results when comparing models with different sets of variables (Paressol 1999). Residual sum of squares (RSS) is the standard error estimate of a regression model and AIC the amount of information lost in the specific model. Thus, the smaller the RSS and AIC, the better the model (Chave *et al*. 2001; Burnham and Anderson 2002; Agresti and Franklin 2007; Basuki *et al*. 2009). Because the the ratio of n to k, where n is the sample size and k is the number of independent variables, is less than 40, an adjusted AIC was calculated and expressed as AICc, as shown in Eq. 5.

$$\text{AICc} = n \log\left(\frac{\text{RSS}}{n}\right) + 2k + \frac{2k(k+1)}{(n-k-1)} \tag{5}$$

A model that has the lowest value of AICc is considered to be the best fit model. The accuracy of AGB models (1) to (4) was validated using three indices, *viz.* root mean square (RMSE in kg), mean bias (in kg), and fit index (FI), in accordance with Hosoda and Iehara (2010) and Battulga *et al*. (2013):

$$RMSE \text{ (kg)} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y_i')^2}{n}} \tag{6}$$

$$Bias \text{ (kg)} = \frac{\sum_{i=1}^{n}(y_i - y_i')}{n} \tag{7}$$

$$FI = 1 - \frac{\sum_{i-1}^{n}(y_i - y_i')^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2} \tag{8}$$

where y_i, $\overline{y}$, and n are observed biomass, mean of observed biomass, and sample size, respectively, and y' is the estimated biomass using Eqs. (1) to (4). A model that has the smallest value of RMSE and highest FI is considered as the most appropriate model.

Determination of Carbon Stock

The best fit total AGB equations were then used to determine the total AGB of the all trees in the five sampling plots with stem DBH as shown in Table 1. Then, carbon (C) stocks were obtained by converting AGB to stored carbon fractions (CF) by multiplying by 0.47 (IPCC 2006) expressed in biomass per hectare. The amount of carbon dioxide (CO_2) sequestered was calculated by multiplying by the ratio of CO_2 to C, which is 3.667, and then by dividing the product by the age of the tree to obtain the amount of CO_2 sequestered per year.

Table 1. Mean Diameter at Breast Height and basal area of Five Sampling Plots, each from *Acacia* Hybrid and 2nd Generation *Acacia mangium* of 10-year-old Stands

Variant	Plot	N	Mean DBH ± standard error (cm)	Mean Basal area ± standard error (m²)
Acacia hybrid	1	45	23.3±0.9	0.0455 (0.0036)
	2	59	22.8±0.8	0.0437 (0.0028)
	3	29	21.1±0.8	0.0364 (0.0028)
	4	21	22.1±0.9	0.0398 (0.0037)
	5	21	21.5±1.4	0.0395 (0.0046)
	Total	175		
2nd generation *A. mangium*	1	47	23.4±0.8	0.0454 (0.0029)
	2	77	21.4±0.6	0.0380 (0.0021)
	3	41	23.9±0.9	0.0474 (0.0034)
	4	60	22.0±0.7	0.0403 (0.0024)
	5	75	22.0±0.7	0.0420 (0.0024)
	Total	300		

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RESULTS AND DISCUSSION

Aboveground Biomass Models

The DBH of felled *Acacia* hybrid and second generation *A. mangium* ranged from 12.8 to 40.9 cm and 11.6 to 41.5 cm, respectively. Figure 1 shows a scatterplot of the relationship between biomass and DBH. The results of curve fitting analyzed for total tree AGB for *Acacia* hybrid and second generation *A. mangium* are shown in Tables 2 and 3. The equations showed high R^2 values, indicating that the curves using DBH as the independent variable fitted well with the AGB. In all cases, models (1) to (3) explained more than 90% (and model 4 more than 80%) of the total variation of AGB. Comparison of models revealed that model (2) yielded the smallest AIC. Thus, it was considered as the best fit model for estimating the total AGB of *Acacia* hybrid and 2nd generation *Acacia mangium*. Evaluation of validation indexes showed that model (2) gave the lowest values of RMSE and the highest FI. Further analyses showed that models (1) and (4) resulted in negative biomass values following substitution of DBH into each model, suggesting that these models are not suitable. It was also found that there were limitations in applying the linear and logarithmic models for calculating biomass of small trees with diameters less than 15 cm. Model (3) was also excluded based on its index values.
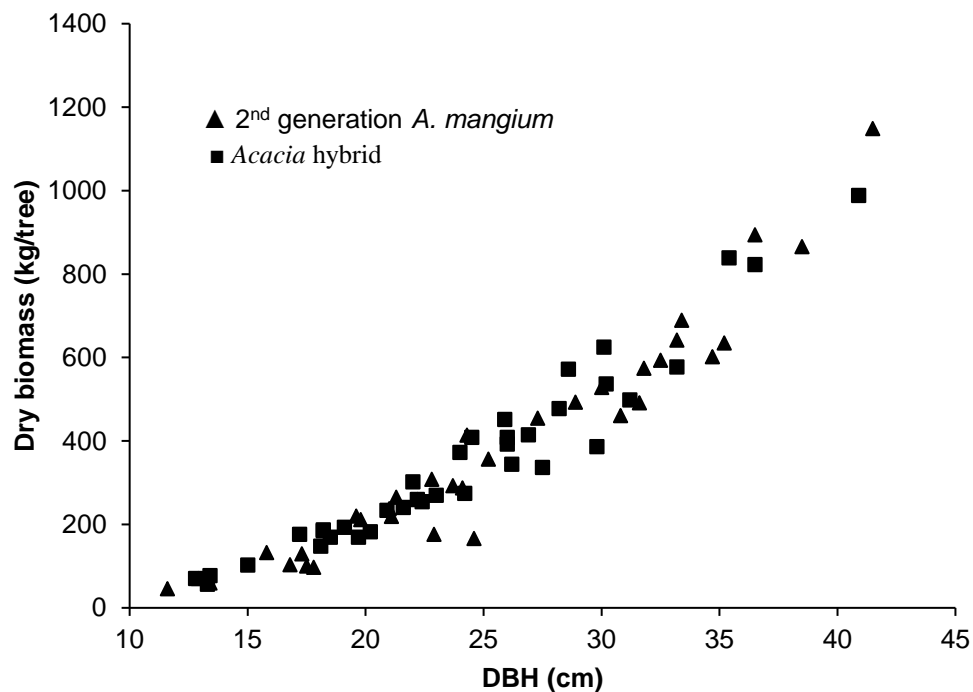

Fig. 1. Scatterplot of biomass per tree and DBH for Acacia hybrid and 2nd generation *A. mangium*

The results showed that model (2), which is in the power form, resulted in the smallest RMSE and highest FI values, indicating that it is the best fit model in estimating total AGB (Table 4). Therefore, the most accurate biomass equation was determined to have a form of $y = ax^b$ where x is predictor variable (DBH), a is y the intercept, and b is regression coefficient.

Table 2. Whole Tree AGB Models for *Acacia* hybrid (n = 36) and Second Generation *Acacia mangium* (n = 35) with Respective Coefficients of Determination (R^2) and Statistical Significance Values (*P*-values)

Variant	No.	Model	Form	R^2	*P*-value
Acacia hybrid	1	$y = 31.775D - 413$	Linear	0.92	<0.0001
	2	$y = 0.175D^{2.350}$	Power	0.96	<0.0001
	3	$y = 26.927e^{0.0981D}$	Exponential	0.91	<0.0001
	4	$y = 712.25\ln(D)-1885.9$	Logarithm	0.84	<0.0001
2nd generation *A. mangium*	1	$y = 33.32D - 459.85$	Linear	0.90	<0.0001
	2	$y = 0.1173D^{2.454}$	Power	0.94	<0.0001
	3	$y = 22.341e^{0.101D}$	Exponential	0.91	<0.0001
	4	$y = 754.32 \ln(D) - 2017.1$	Logarithm	0.81	<0.0001
Units in kg for biomass (*y*) and cm for diameter at breast height (D)					

Table 3. Whole Tree AGB Models for *Acacia* hybrid (n = 36) and Second Generation *Acacia mangium* (n = 35) with their Respective Coefficients of Determination (R^2), Residual Sum of Squares (RSS), and Akanke Information Criterion (AIC)

Variant	No.	Model	R^2	RSS	AICc	ΔAICc*
Acacia hybrid	1	$y = 31.775D - 413$	0.92	136622	281.0	398.6
	2	$y = 0.175D^{2.350}$	0.96	0.702	-117.6	0
	3	$y = 26.927e^{0.0981D}$	0.91	1.468	-94.8	22.9
	4	$y = 712.25\ln(D)-1885.9$	0.84	269691	259.9	377.5
2nd generation *A. mangium*	1	$y = 33.32D - 459.85$	0.90	244560	270.0	361.1
	2	$y = 0.1173D^{2.454}$	0.94	1.299	-94.4	0
	3	$y = 22.341e^{0.101D}$	0.91	2.022	-81.1	10.0
	4	$y = 754.32 \ln(D) - 2017.1$	0.81	470652	1141.2	1232.3
* ΔAICc is the difference between the AIC of models (1) to (4)						

Previous studies have also shown that power functions were able to estimate AGB with considerable goodness of fit (Crow 1978; Fownes and Harington 1991; Overman *et al*. 1994; Ketterings *et al*. 2001; Aboal *et al*. 2005; Zianis *et al*. 2005; Cienciala *et al*. 2006). Power function models also express the allometry between different parts of the plant, such as the proportionality in the relative increments between stem biomass and girth of the trees (Parde 1980).

Allometric equations of AGB in logged-over tropical rainforests also showed power functions to be most appropriate functions to model their AGB (Kenzo *et al*. 2009b). Allometric equations for estimation of *A. mangium* AGB using DBH as the only predictor also yielded the power function form (Hiratsuka *et al*. 2003; Banaticla *et al*. 2005). Hosoda and Iehara (2010) reported that a power equation was the most suitable equation for using DBH and height as independent variables for estimating AGB of *Cryptomeria japonica*, *Chamaecyparis obtuse*, and *Larix kaempferi* even-aged stands. The power function was also found to make the best model for predicting stem biomass of *Larix sibirica* (Battulga *et al*. 2013).

Table 4. Indices of AGB Models

Variant	Model	RMSE (kg)	Bias (kg)	FI
Acacia hybrid	1	61.6	-0.0014	0.977
	2	53.5	0.3127	0.982
	3	104.4	-6.2	0.934
	4	86.6	0.0032	0.955
2nd generation *A. mangium*	1	82.4	-0.0093	0.900
	2	57.3	4.3	0.952
	3	86.6	-5.4	0.892
	4	114.4	-0.1230	0.813

Aboveground Biomass and Carbon Stock Estimation

The power functions $y = 0.1173D^{2.454}$ and $y = 0.175D^{2.350}$ were used to estimate AGB of each tree in all five plots (Table 1) of second generation *A. mangium* and *Acacia* hybrid, respectively. Total AGB were expressed in megagram (Mg) and converted into Mg per hectare (Mg ha^{-1}) (Table 5). The estimates showed that AGB of second generation *A. mangium* was higher (178.9 Mgha^{-1}) than that of *Acacia* hybrid (113.3 Mg ha^{-1}). On the average, stem biomass of both variants accounted for 80% to 85% of the total biomass. Branch and leaf biomasses accounted for 12% to 16% and 3% to 8%, respectively.

Carbon stocks were calculated by using the carbon conversion factor of 0.47 (IPCC 2006). Fengel and Wegener (1983) noted that C content in various wood species differs slightly but averaged at 50% and was always found to be between 45% and 50% (Schlesinger and Bernhardt 2013). Second generation *A. mangium* showed higher AGB compared to *Acacia* hybrid and, thus, gave higher total aboveground carbon stock values per hectare; C content depends on biomass content (Brown and Lugo 1992). It was estimated that second generation *A. mangium* and *Acacia* hybrid are able to stock an average of 8.4 Mg per ha and 5.3 Mg per ha of C in a year, respectively (Table 5).

The amount of CO_2 sequestered was determined by multiplying the amount of carbon stocks by 3.667. Second generation *A. mangium* sequestered CO_2 about 1.6 times more than *Acacia* hybrid. The results indicated that 10-year-old second generation *A. mangium* and *Acacia* hybrid had sequestered 308.3 Mgha^{-1} and 195.3 Mgha^{-1} of CO_2. On average, second generation *A. mangium* and *Acacia* hybrid can sequester 30.8 Mg ha^{-1} and 19.5 Mg ha^{-1} of CO_2, respectively, annually for 10 years (Table 5).

Table 5. Total Aboveground Biomass, C-stock, and CO_2 Sequestered in 10 years Old *Acacia* Hybrid and Second Generation *Acacia mangium*

Variant	AGB per hectare (Mg)	Aboveground C stock (Mgha^{-1})	Mean annual C increment (Mgha^{-1})	CO_2 sequestered (Mgha^{-1})	Mean annual CO_2 sequestered (Mgha^{-1}yr^{-1})*
Acacia **hybrid**	113.3	53.3	5.3	195.3	19.5
2nd generation *Acacia mangium*	178.9	84.1	8.4	308.3	30.8
*Mg = megagram = 1000 kg					

Considerable variations exist in the aboveground C stock and carbon sequestration rate with respect to forest types and their geographical locations. For instance, higher above-ground C was found in lowland forests compared to forests in hilly regions (Baral

et al. 2009). Comparisons of annual C stocking by different plantation species around the region are shown in Table 6. These results showed that the estimates of annual C stock in the second generation *A. mangium* and *Acacia* hybrid in this study were comparable with estimates of annual C stock in *Eucalyptus tereticornis, Populus deltoides* (Kaul *et al*. 2010), and *A. mangium* (Halenda 1989; Herdiyanti and Sulistyawati 2009).

Table 6. Comparison of Mean Annual C-stocks of Several Species According to Age and Plantation Type

Species	Annual C Storage ($Mg\ ha^{-1}yr^{-1}$)	Age (Years)	Plantation Type	Reference
Acacia mangium	8.5	6.8	Short rotation plantation	Halenda (1989)
Elaeis guineensis	1.7	23	First rotation oil palm plantation	Khalid *et al.* (1999)
Eucalyptus tereticornis	6	9	Short rotation plantation	Kaul *et al.* (2010)
Populus deltoides Marsh	8	9	Short rotation plantation	Kaul *et al.* (2010)
Acacia mangium Willd	10.4	7	Short rotation plantation	Herdiyanti and Sulistyawati (2009)
Acacia mangium	10.0	6 to 8	Short rotation plantation	Morikawa *et al.* (2002)
2[nd]generation *Acacia mangium*	8.4	10	Short rotation plantation	This study
Acacia hybrid	5.3	10	Short rotation plantation	This study

Higher net annual CO_2 sequestration rates were observed for fast growing, short rotation *A. mangium*, *Eucalyptus tereticornis,* and *Populus deltoids* plantations compared to *Elaeis guineensis* (Table 6). Fast growing, short rotation plantations have the ability to show high net annual carbon sequestration rates achieved during only a short period. Baishya *et al*. (2009) noted that sal (*Shorea robusta*) plantations had higher AGB (406.4 $Mgha^{-1}$) than natural tropical semi-evergreen forests (324 $Mgha^{-1}$). Short rotation forest plantations are also capable of sequestrating more CO_2 than oil palm plantations and secondary forests. The annual carbon storage found here were about two to three times higher than that of regenerating secondary forests in Sarawak. Carbon sequestration reported by Jespen (2006) were 1.1 and 3.2 $Mg\ ha^{-1}yr^{-1}$ in 5.5 and 3.2 years old secondary forest, respectively. Early successional secondary forests of 4 to 5.5 years after shifting cultivation recorded annual carbon storage of 5.2 and 6.7 $Mg\ ha^{-1}yr^{-1}$, respectively (Kenzo *et al*. 2010).

Although the present work is based on data obtained from one age class, the regression models should be able to reliably predict the AGB and C content of second generation *A. mangium* and *Acacia* hybrid trees aged 8 years old and older. The model is based on the fact that plantation species grow rapidly in the early growing phase and then begin to level-off after 8 years from planting. Previous studies also showed that *A. mangium* trees grow steadily until their 5th year to 8th year and tend to show no net or even decrease in growth thereafter (Heriansyah *et al*. 2003; Krisnawati *et al*. 2011).

High rates of carbon sequestration can be expected in the first few years of tree growth. In *A. mangium*, the largest amount of C sequestered occurs during the first 5 years to 8 years. If the trees are harvested and the wood is utilized for long-term products like housing timbers and furniture, then the sequestered C will remain stored. When new trees are planted they will remove additional CO_2 from the atmosphere. Therefore, establishing forest plantations out of idle and degraded lands can be a mitigating measure for atmospheric CO_2. For Malaysia, *A. mangium* plantations' role as a CDM for climate change mitigation as well as in economic returns will be the driving factor for future forest plantation projects.

CONCLUSIONS

1. The power model was determined as the most appropriate model for estimating total AGB of *Acacia* hybrid and second generation *A. mangium* plantations in Sarawak.

2. Second generation *A. mangium* plantations were shown to be capable of sequestering 30.8 Mg ha^{-1}yr^{-1} CO_2 compared to *Acacia* hybrid, which were shown to be capable of sequestering only 19.5 Mgha^{-1}yr^{-1}.

3. Overall, this study showed the ability of short rotation plantations to remove carbon from the atmosphere. Hence, large-scale forest plantations not only give benefits for economic reasons, they also play an important role as carbon sinks and their capabilities can be enhanced by planting new trees. For these reasons carbon sequestration and wood volume production will be major objectives of future forestry projects.

4. For meaningful forest plantation projects there should be no natural forest conversion and it must be carried out only in deforested or degraded land areas.

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