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Assessment of biophysical properties of Royal Belum tropical forest, Malaysia

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The Royal Belum forest reserve is one of the oldest tropical rainforests in the world and it is one of the largest virgin forest reserves in Malaysia. However, not many studies have been conducted to understand the ecology of this forest. In this study we estimated the aboveground biomass (AGB) of the forest using diameter at breast height (DBH) and height of trees (*h*), tree species and hemispherical photographs of tree canopy. We estimated AGB using five allometric equations. Our results demonstrated that the AGB given by the one tree species specific allometric equation does not show any significant differences from the values given by the non-tree species specific allometric equations at tree and plot levels. The AGB of *Intsia bijuga* species, *Koompassia malaccensis* species and *Shorea* genera were comparatively higher, owing to their greater wood density, DBH and *h*. This has added importance because some of these species are categorized as threatened species. Our results demonstrated that mean AGB values in this forest (293.16 t ha^{-1}) are the highest compared to some studies of other areas in Malaysia, tropical Africa and tropical Bazilian Amazonia, implying that the Royal Belum forest reserve, is an important carbon reservoir.

Keywords: Tropical forest, Royal Belum, forest reserve, aboveground biomass, carbon stock, Malaysia

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Introduction

The Royal Belum forest reserve in Perak State in Peninsular Malaysia has been recognized as one of the oldest tropical rainforests in the world. It is believed to have existed from 130 million years ago; this makes it even older than the forests in the Amazon and the Congo (MNS, 2005). It is also one of the largest virgin forest reserves in Malaysia. The forest (117 500 ha) is identified as an environmentally sensitive area (ESA)-Rank 1, where development, agriculture and logging are not allowed except for low impact tourism, research and education purposes. The forest is protected under the Malaysian National Forestry Act and the Northern Corridor Implementation Authority has also declared this forest as a spot for ecotourism. Nevertheless, this forest has not been explored fully to understand its biodiversity, ecological significance and socio-economic aspects.

Managing tropical forests for the best outcomes for sequestering carbon and promoting climate change mitigation is also becoming increasingly important (Kho & Jepsen, 2015; Zaki & Latif, 2016). Thus, it is important to quantify and understand the patterns and processes of tropical ecosystem carbon dynamics so that future policies are

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based on a sound scientific understanding and we are able to better manage and secure the resources in the tropical forests of Malaysia. Sabah state in Eastern Malaysia (in Borneo) for example has carried out monitoring, measurements, reporting and verification (M&MRV) of carbon dynamics as part of the efforts in REDD+ that partially focused on mapping and monitoring of tropical forest carbon stocks over large geographical areas. AGB mapping is essential because AGB is a significant component of the global carbon cycle (IPCC, 2007). In Malaysia, AGB has previously been estimated at the Forest Research Institute of Malaysian Forest Reserve (Hamdan *et al.*, 2011), rainforest and oil palm (Morel *et al.*, 2011) in Sabah Malaysia, and at the Matang Mangrove Forest Reserve (Hamdan *et al.*, 2014) in Peninsular Malaysia. However, there is no comprehensive study to map the biomass of the Royal Belum forest reserve despite the fact that the AGB of the region is important to determine the potential carbon emission from deforestation and the potential carbon sequestration by the forest.

AGB can be estimated using destructive and non-destructive methods (Zaki *et al.*, 2016). Estimating AGB using the destructive method involves felling trees and oven drying tree components such as leaves, stem, flowers, etc. in the laboratory to determine the total dry weight of trees. Carbon stored in the above ground components of trees represent about 47 per cent of the total dry weight (IPCC, 2003). Although this method gives accurate AGB estimates, it is destructive and not sustainable. Therefore, allometric equations are crucial for estimating AGB in non-destructive and sustainable ways. An allometric equation is a mathematical function that is based on the relationship between AGB and measurable biometric variables such as diameter at breast height (DBH), height (h), etc. Although many allometric equations are available for tropical forests, only a few are suitable to be used in the primary rainforest and the environment of Malaysia, such as those of Kato *et al.* (1978), Ketterings *et al.* (2001), Chave *et al.* (2005), Basuki *et al.* (2009) and Kenzo *et al.* (2009). These allometric equations were developed in rainforests in Malaysia or Indonesia, which could also provide relatively accurate AGB estimates for the Royal Belum forest reserve that has a similar environment and ecosystem. Although different allometric equations with different biometric variable inputs were developed for the region, uncertainties remain on the significant differences between the equations and their suitability for the forest. Therefore, in this study we have tested the differences among the various allometric equations developed to estimate the AGB of the tropical forest. Moreover, there are only a few studies looking at species-level AGB information in the tropical moist and wet forests (Chave *et al.*, 2005), and dry forests (Chave *et al.*, 2005, Hernandez-Stefanoni *et al.*. 2014) but no studies have been conducted on the virgin forest reserves in Malaysia. Therefore, in this study we also assessed the AGB of various species to understand their potential for storing atmospheric carbon for better carbon management and climate mitigation.

The relationship of AGB with canopy retrieved parameters from the non-destructive methods, i.e. hemispherical photography technique, namely plant area index (PAI) and fraction of canopy cover (Weiss & Baret, 2010) remains unclear for the tropical virgin forest, although canopy is an important component that is contributing to the AGB. The potential of the derived PAI and fraction of canopy cover from the hemispherical photography technique for AGB estimation at the plot scale for virgin forest needs to be investigated, since there is great interest in using airborne and spaceborne remote sensing for monitoring canopy leaf area index on a large scale. Such investigation is important to be carried out beforehand to test the feasibility of PAI and canopy closure as the indicator of biomass for this region.

In addition, this study also assessed the disturbance level of the forest based on a theoretical model as proposed by Simini *et al.* (2010) and Anfodillo *et al.* (2013). Forest disturbance is caused by various factors such as wind, insect infestations, wildfires etc. Assessing the disturbance level of the forest is important because increasing disturbances could strongly impact the forest carbon storage, an important ecosystem service in the context of climate change mitigation (Seidl *et al.*, 2014). It is reported that the distribution of tree size and the degree of slope of the size distribution curve in the range of negative power law can estimate the level of disturbance in the forest (Anfodillo *et al.*, 2013). Disturbances alter the degree of slope of the size distribution curve as reported in some disturbed forests of temperate regions (Anfodillo *et al.*, 2013). In undisturbed forests, the degree of slope of the size distribution curve is steeper whereas in disturbed forests, the slope of the size distribution curve is less steep. This finding can be a diagnostic tool for determining whether the Royal Belum forest reserve is undisturbed (i.e. virgin forest reserve) or disturbed (e.g. due to natural disaster, or anthropogenic activities etc.). The findings of this study have the potential to encourage the Malaysian Department of Forestry and the Perak State Development Corporation to develop tree inventory information for this forest reserve as part of their efforts in M&MRV of carbon dynamics in REDD+, and to enhance our understanding of its role in the regional carbon cycle.

In brief, the objectives of this study were to:

1. estimate AGB using allometric equations at plot and species levels, and test the significant difference between the equations for the Royal Belum forest;
2. investigate the relationships between AGB and plant area index and fraction of canopy cover; and
3. determine whether the Royal Belum forest is disturbed or undisturbed.

Study area

The study area is located in the Royal Belum forest reserve (117 500 ha) in Gerik, Perak State of Peninsular Malaysia (Figure 1). The Royal Belum forest reserve includes a dense *dipterocarp forest* and the Temenggor Lake. The area remains warm and humid throughout the year; the range of temperature is between 23°C and 32°C and the average annual rainfall is 2205 mm. The altitude of the study area is 260–1533 m (*Malaysiahere*, 2014). The majority of the plant species are trees and some rare plants species such as the *Rafflesia* are found in the forest. The Royal Belum forest reserve is home to many endangered animal species such as the leopard cat, black panther and Sumatran Rhinoceros (*Malaysiahere*, 2014). From an environmental point of view, large trees found in the tropical forests help prevent flooding, soil erosion and landslides during heavy downpours.

Data and methodology

Data collection

A total of 39 plots were established for this study using an equalized random sampling method. Six plots were established in secondary forests and the remaining 33 in primary forest. The secondary forest plots were located outside the reserve, next to the East–West highway of Peninsular Malaysia and are the product of regrowth after logging occurred as part of the highway construction in 1970 (Figure 1).

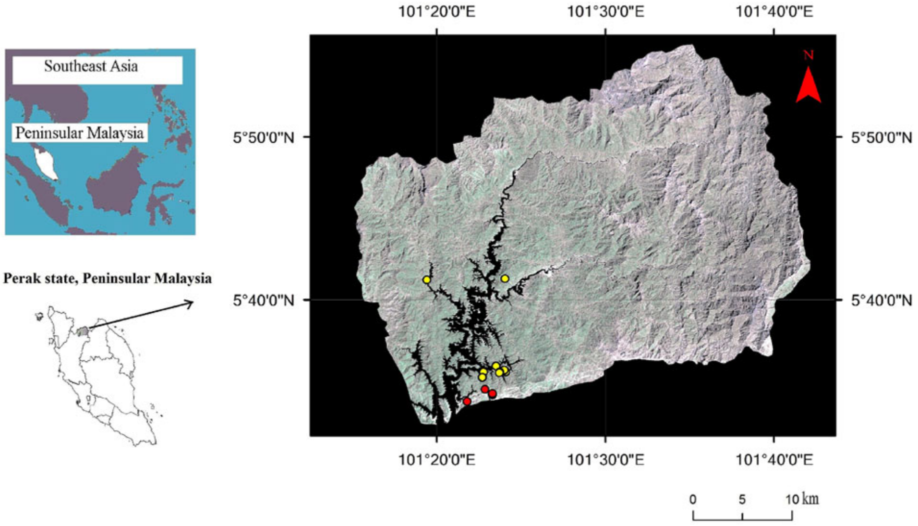

Figure 1. *The Royal Belum reserve forest in Perak State, Peninsular Malaysia, as shown by a Landsat 8 image dated 4 February 2014 (Red, band 6, Green, band 5, Blue, band 4). The locations of field plots are shown by dots. The yellow dots show the locations of field plots in the Royal Belum forest reserve (primary forest). The red dots show the locations of field plots in the secondary forest located next to the East–West highway of Peninsular Malaysia.*

Source: **Map prepared by Tan Kian Pang using Landsat satellite image downloaded from USGS Earth Explorer. Available online: http://earthexplorer.usgs.gov/ (accessed on 5 February 2016).**

Each of the plots was circular with a diameter of 25 m and an area of approximately 500 m^2. The biometric parameters, namely, (i) diameter at breast height DBH (cm), measured at about 1.3 m above ground, (ii) height h (m), (iii) tree species, (iv) fraction of canopy cover (per cent), and (v) plant area index (m^2 m^{-2}, defined as the plant area per unit ground area), were collected from trees in each plot. A total of 954 trees (mean 24 trees per plot) were sampled. We identified 790 trees belonging to 40 species/binomials, but the species of 61 trees were unidentified. The remaining 103 trees were identified into six genera only.

We measured only trees with DBH ≥10 cm within the plot, following the Malaysian Forest Resources Assessment (FRA) methods (FRA, 2010). As for trees near the edge of a plot, the stems of the trees may fall within the plot and their canopies may partially extend out of the plot area. In this case the trees are considered partially (e.g. 1/10–1/2) contributing to the AGB in relation to the fraction of the crown within the plot. In this study, we did not correct the biomass due to the ‘edge issue’ since the Royal Belum forest reserve has a dense canopy, which means that there are trees outside the plot whose canopies may partially fall inside the plot area in many cases. We acknowledge that the limitation in our sampling method for ‘edge issue’ may result in some overestimation in AGB. Because of the signal interference by the dense forest canopy, the locations of the plots were recorded by a differential GPS at open areas (such as river bank and boundary of the forest), using total stations to determine the coordinates of the locations of plots under the canopy. The height was measured by Leica Disto D5. In addition, hemispherical photos of tree canopies were taken for each plot, vertically in nadir facing the sky, by using automatic and manual modes of the CANON EOS1100D digital camera fitted with a Raynox circular fisheye conversion lens with focal length of 58 mm. The upper part of the hemispherical photo was oriented towards the north using a compass. Each photo was pre-processed by gamma adjustments, masking unwanted objects (sun) and classified into two classes, i.e. sky and trees. The photos were processed to derive plant area index and fraction of canopy cover for each plot using CANEYE V6.314 software (Weiss & Baret, 2010). Taking a hemispherical photo facing upward to the canopy in a tropical forest would include leaves, branches, stems, etc. Therefore the definition of plant area index (PAI) which describes the plant area (leaves, branches, and stems) per unit ground area was more suitable for this study, instead of using leaf area index (LAI) (Weiss & Baret, 2010). Estimating PAI using the hemispherical method is based on gap fraction measurements that measure the transmittance or the penetration of light through vegetation to reach the ground surface without contact with vegetation components. PAI was estimated using the Poisson equation (Equation 1) (Nilson, 1971; Weiss & Baret, 2010).

$$P(\theta,\phi) = \exp\{-\lambda\, G(\theta,\phi)\,(\mathrm{PAI})/\cos\theta\} \tag{1}$$

where the gap fraction $P(\theta,\ \phi)$ in the direction of zenith (θ) and azimuth (ϕ) has an exponential (exp) relationship with the clumping index (λ) which is the degree of random leaf spatial distribution, the projection coefficient of leaf angular distribution $G(\theta,\ \phi)$ in the direction of θ, ϕ that influences the transmittance through the vegetation at various angles, as well as PAI. The fraction of canopy cover is defined as the fraction of canopy per unit ground area. It is estimated by one minus the gap fraction (Equation 2).

$$\text{Fraction of canopy cover} = 1 - P(\theta,\phi) \tag{2}$$

Estimating AGB and carbon stocks

The Royal Belum forest contains many species of flora. Therefore, the selection of allometric equations that were developed for local tropical forests type and/or species is crucial for estimating an accurate AGB. In this study, we used DBH, h and ρ for estimating the AGB by using existing allometric equations developed in various areas in Malaysia and Indonesia (Table 1).

It should be noted that some of the published allometric equations are purely empirical and are based on fitting the data from a set of ground measurements. However, it is possible to determine an allometric equation on the basis of physical principles. Thus estimating AGB can be done by using a general geometrical equation that assumes the tree taper does not change as trees get larger (Equation 3).

$$\mathrm{AGB} = \mathrm{F} \times \rho \times \left(\pi\, \mathrm{DBH}^2/4\right) \times \mathrm{h} \tag{3}$$

where AGB (kg tree^{-1}) is the product of F (a coefficient for tree taper), ρ, the wood density (g cm^{-3}) which is the ratio of the mass of the oven dried wood and the fresh (wet) volume, DBH (cm) and h (m). The value of F is 0.0333 and 0.1 for a tree trunk with perfect conical and pole shapes respectively (Chave *et al.*, 2005). (Strictly speaking this is not quite true; for a perfect cone the value of F is 1/30 and the diameter should be the diameter at the ground rather than the DBH). The value of F is 0.06 for a broadleaf forest (Cannell, 1984). The allometric equation of Chave *et al.* (2005) is based on this physical model where they use a constant value of $F \times \pi\ /4$ of 0.0509, which

Table 1. Allometric equations for estimating aboveground biomass.

No.	Allometric equations (kg tree^{-1})	Study area	References
1	$AGB = M_S + M_b + M_l$ $M_S = 0.0313 \times (DBH^2 h)^{0.9733}$ $M_b = 0.136 \times (M_S)^{1.070}$ $1/M_{l\,=}\ 1/\ (0.124 M_S^{0.794}) + 1/125$	Pasoh forest reserve, Peninsular Malaysia	Kato *et al.* 1978
2	$\ln(AGB) = 2.59 \times \ln(DBH) - 2.75$	Sumatra, Indonesia	Ketterings *et al.* 2001
3	$AGB = 0.0509 \times (\rho\ DBH2\ h)$	27 study sites in the tropics which included Pasoh forest reserve, Peninsular Malaysia	Chave et al. 2005
4	$\ln(AGB) = 2.196 \times \ln(DBH) - 1.201$	Kalimantan, Indonesia	Basuki *et al.* 2009
5	$AGB = 0.0829 \times DBH^{2.43}$	Malaysia Borneo	Kenzo et al. 2009

Where AGB = aboveground biomass (kg tree^{-1}), DBH = diameter at breast height (cm), h = height (m), M_S = dry mass of stem (kg), M_b = dry mass of branches (kg), M_l = dry mass of leaves (kg), ρ = wood density (g cm^{-3}).

Source: Table prepared by Tan Kian Pang and Kasturi Devi Kanniah using allometric equations from Kato *et al.* (1978), Ketterings *et al.* (2001), Chave *et al.* (2005), Basuki *et al.* (2009) and Kenzo *et al.* (2009).

corresponds to a value of F of 0.0648. There is some extent to which this physical model is involved in the allometric equation of Kato *et al.* (1978). The other three allometric equations in Table 1 are simply empirical and do not involve the height, h, of the trees explicitly at all.

The ρ values for various tree species around the world are available from the global wood density database (Zanne *et al.*, 2009; Chave *et al.*, 2009). First we extracted the ρ values of the known tree species in the Royal Belum forest reserve from the database. We used the average ρ values for species with more than one record in the database and average ρ genera values for trees only identified to that taxonomic level. In this study, ρ ranges between 0.32 to 0.82 g cm^{-3} (mean 0.54 g cm^{-3}) (Table 2). We used the mean ρ value from this study for unknown tree species.

We summed the AGB of all trees (in kg tree^{-1}) to obtain the total AGB for each plot, and converted it into t ha^{-1}. The carbon content values are assumed to be 47 per cent of AGB (IPCC, 2003). We compared the results of the AGB from all the allometric equations to see if there was any significant differences among them.

Results and discussion

Plot based AGB

The DBH of the 954 trees measured ranged between 10 and 228.9 cm (mean 24.22 cm) and h ranged between 2.18 and 49.46 m (mean 15.33 m). The results of AGB estimations using various allometric equations for the 39 plots are shown in Figure 2(a). We averaged the AGB from these five equations and the results are shown in the upper right (inset) of Figure 2(a). Plot 10 has a very high AGB derived from allometric equations (see Figure 2 (a)) because this plot has one very large tree with DBH of 228.9 cm and height, h, of 49.46 m. High AGB (t tree^{-1}) values were obtained for this big tree as calculated from Kato *et al.* (1978) (58.57 t tree^{-1}), Ketterings *et al.* (2001) (82.64 t tree^{-1}), Chave *et al.* (2005) (74.53 t tree^{-1}), Basuki *et al.* (2009) (45.73 t tree^{-}1) and Kenzo *et al.* (2009) (44.93 t tree^{-1}).

In previous studies, the DBH values used for developing the allometric equations range between 5 and 156 cm (Chave *et al.*, 2005), therefore, the very large tree with

Table 2. The ρ values used for various tree species and genera in the Royal Belum forest reserve, Malaysia.

Species	ρ (g cm^{-3})	Genera	ρ (g cm^{-3})
Aquilaria malaccensis	0.32	*Goniothalamus*	0.44
Sapium baccatum	0.34	*Mallotus*	0.5
Dyera costulata	0.34	*Scaphium*	0.5
Spondias dulcis	0.37	*Saraca*	0.55
Mastixia trichotoma	0.39	*Shorea*	0.55
Pterocymbium javanicum	0.4	*Lithocarpus*	0.67
Cratoxylum arborescens	0.43		
Endospermum malaccense	0.46		
Pimelodendron amboinicum	0.5		
Pentaspadon motley	0.5		
Averrhoa bilimbi	0.5		
Baccaurea motleyana	0.51		
Acacia mangium	0.51		
Artocarpus rigidus	0.51		
Shorea atrinervosa	0.55		
Vatica rassak	0.55		
Mangifera indica	0.55		
Shorea leprosula	0.55		
Shorea platycarpa	0.55		
Anisoptera costata	0.55		
Castanopsis inermis	0.55		
Copaifera palustris	0.56		
Horsfieldia superb	0.56		
Syzygium polyanthum	0.56		
Dendrobium crumenatum	0.56		
Calophyllum inophyllum	0.58		
Alstonia angustifolia	0.61		
Shorea parvifolia	0.61		
Palaquium gutta	0.62		
Hopea beccariana	0.65		
Intsia palembanica	0.66		
Fagraea fragrans	0.69		
Ixonanthes icosandra	0.7		
Nephelium lappaceum	0.71		
Hopea glaucescens	0.71		
Intsia bijuga	0.71		
Scorodocarpus borneensis	0.72		
Dipterocarpus fagineus	0.75		
Koompassia malaccensis	0.76		
Dialium indum	0.82		

Source: Table prepared by Tan Kian Pang using data collected in the field.

DBH of 228.9 cm from plot 10 was removed from further analysis and the AGB was re-estimated. The results are shown in Figure 2(b) which is plotted on the same scale as in Figure 2(a). These results are plotted again in Figure 2(c) using a more appropriate scale on the y axis. Figure 2(b) is included because all that we have done is to remove the one very large tree in plot 10. This would have been obscured by the change of scale in Figure 2(c) if Figure 2(b) had not been included. We have separated the 39 plots into secondary and primary forests. The AGB estimated from the primary forests (293.16 t ha^{-1}) was about 7.67 times higher than the secondary forests (38.20 t ha^{-1}) (Table 3).

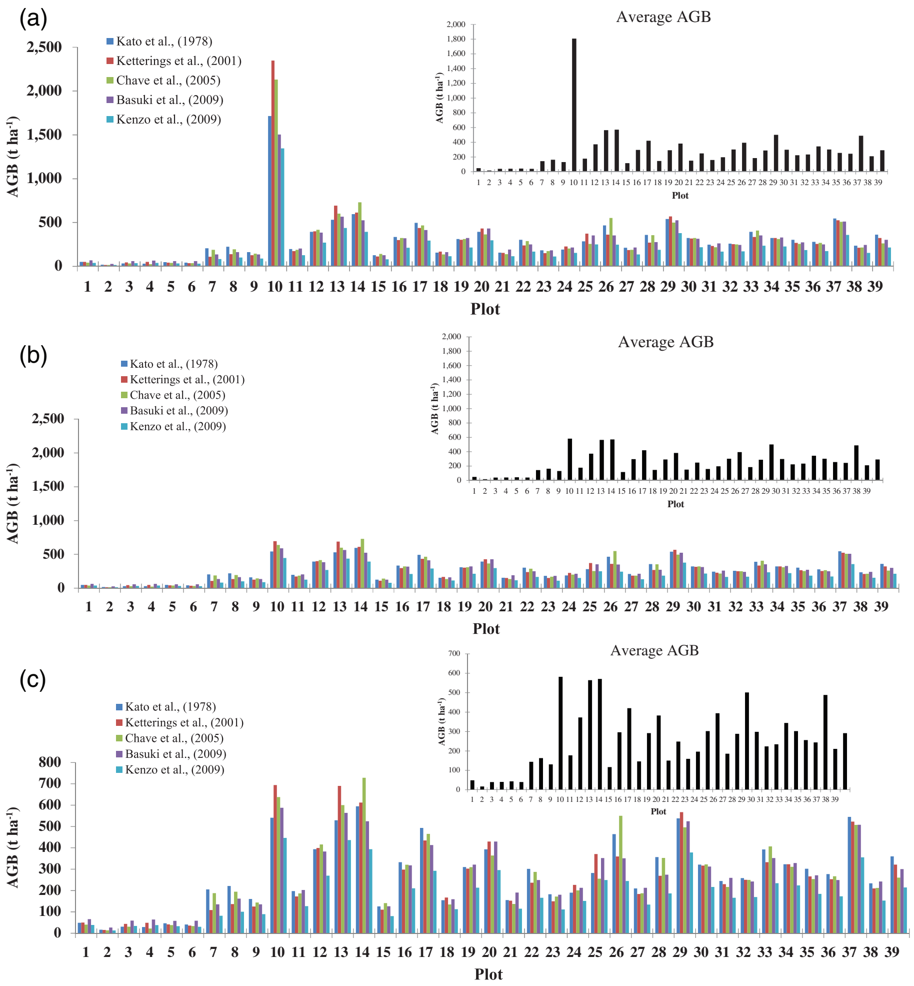

Figure 2. *(a) AGB for 39 plots by using various tropical forest allometric equations. Plot 10 has one big tree (DBH = 228.9 cm) which contributes to high biomass values. The upper right image shows the average AGB from these allometric equations. (b) AGB for 39 plots after excluding the big tree in plot 10 while the AGB values of other plots are similar to Figure 2(a) and it has the same scale on the y axis as in Figure 2(a). (c) AGB for 39 plots are similar to Figure 2(b) but with different scale on the y axis as in Figure 2(b).*
***Source*: Graph prepared by Tan Kian Pang and Kasturi Devi Kanniah using data collected in the field.**

The AGB (t tree^{-1}) at the tree level showed significant differences ($n = 953$, $p = 0.007$, F value = 3.54) among the allometric equations used. Since the estimated mean AGB by the equation of Kenzo *et al.* (2009) gave a high difference in the mean AGB compared to the other equations, we excluded that equation and found that the AGB (t tree^{-1}) as estimated by the equations of Kato *et al.* (1978), Ketterings *et al.* (2001), Chave *et al.* (2005), and Basuki *et al.* (2009) showed no significant difference ($n = 953$, $p = 0.99$, F value = 0.04) among them. Similarly, the AGB (t ha^{-1}) at the plot level showed significant differences ($n = 39$, $p = 0.05$, F value = 2.43) among the five equations used. After excluding the equation of Kenzo *et al.* (2009), no significant difference ($n = 39$, $p = 0.99$, F value = 0.03) was found among the other four

Table 3. AGB (t ha^{-1}) for primary and secondary forests at the Royal Belum forest reserve using various allometric equations.

	Kato *et al.* (1978)	Ketterings *et al.* (2001)	Chave *et al.* (2005)	Basuki *et al.* (2009)	Kenzo *et al.* (2009)	Mean
Primary forest	321.13	309.93	317.67	305.49	211.60	293.16
Secondary forest	35.43	39.18	29.86	55.45	31.11	38.20

Source: Table prepared by Tan Kian Pang using data collected in the field.

equations (Kato *et al.*, 1978; Ketterings *et al.*, 2001; Chave *et al.*, 2005; Basuki *et al.*, 2009). In other words, the tree species specific allometric equation, i.e. Chave *et al.* (2005) does not show significant differences from the non-tree species specific allometric equations, i.e. Kato *et al.* (1978), Ketterings *et al.* (2001), and Basuki *et al.* (2009) at tree and plot levels. The difference between these four equations (Kato *et al.* 1978, Ketterings *et al.* 2001, Chave *et al.* 2005, Basuki *et al.* 2009) is rather low; ranging between 0.5–3.7 per cent. The difference between the allometric equation of Kenzo *et al.* (2009) and the other four allometric equations (Kato *et al.*, 1978; Ketterings *et al.*, 2001; Chave *et al.*, 2005; Basuki *et al.*, 2009) is relatively high; ranging between 31–34 per cent. This could be due to the fact that the allometric equation of Kenzo *et al.* (2009) was developed for logged forests while the other equations were developed for the primary forests.

We compared our results against other previous AGB studies conducted in forests in Malaysia, namely the FRIM replanted forest since 1929 (Hamdan *et al.*, 2011), Pasoh primary forest (Okuda *et al.*, 2004), Pasoh logged forest from the mid-1950s until the early 1970s (Okuda *et al.*, 2004), Matang Mangrove forest (Hamdan *et al.*, 2014), and in tropical Africa which includes Cameroon, Congo and Uganda (Baccini *et al.*, 2008), and the tropical Brazilian Amazonia (Cummings *et al.*, 2002) (Figure 3). We separated our AGB values into secondary and primary forests. Overall, the AGB of the secondary forests in the Royal Belum ranges between 17.06–48.78 t ha^{-1} (mean 38.2 t ha^{-1}) while the AGB of the primary forests in the Royal Belum ranges between 116.77–581.78 t ha^{-1} (mean 293.16 t ha^{-1}). The mean AGB values in this study are 66 per cent higher than Matang mangrove forest (mean 99 t ha^{-1}), 34 per cent higher than the FRIM replanted forest (mean 194 t ha^{-1}), 56 per cent higher than the Ayer Hitam lowland dipterocarp forest in Selangor state, Malaysia (128.99 t ha^{-1}) (Sumareke, 2016), 19 per cent higher than the tropical Africa forest (mean 238 t ha^{-1}), but 16 per cent lower than the tropical Brazilian Amazon forest (mean 341 t ha^{-1}) and 6 per cent lower than the Pasoh primary forest (mean 310 t ha^{-1}). Nevertheless, the Royal Belum forest reserve has recorded the highest AGB (581.78 t ha^{-1}) compared to the other forests (Figure 3).

AGB at tree species level

Of the five allometric equations that we have considered, only that of Chave *et al.* (2005) included ρ. This allowed us to estimate AGB on the basis of tree species level as opposed to mixed AGB values at the plot level. When comparing trees with similar DBH and h, the tree with higher ρ had greater AGB compared to trees with lower ρ (Chave *et al.*, 2005). From our data, *Dialium indum* tree species had the highest ρ (0.82 g cm^{-3}) while *Aquilaria malaccensis* had the lowest ρ (0.32 g cm^{-3}).

Among the species, *Baccaurea motleyana* has the lowest AGB $tree^{-1}$ (0.03 t $tree^{-1}$) whereas *Intsia bijuga* tree species has the highest AGB $tree^{-1}$ (8.15 t $tree^{-1}$) (Figure 4(a)).

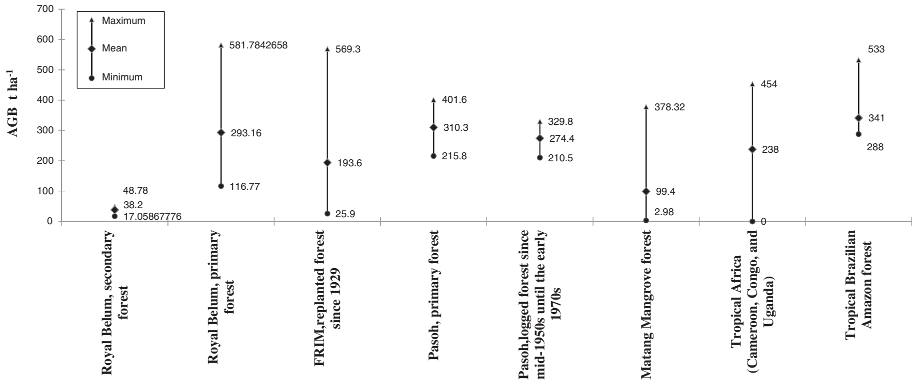

Figure 3. *The AGB values (t ha^{-1}) from various studies in Malaysia, tropical Africa and tropical Brazilian Amazonia.*
Source: **Graph prepared by Tan Kian Pang and Kasturi Devi Kanniah using data collected in the field and data obtained from Hamdan** ***et al.*** **(2011); Okuda** ***et al.*** **(2004); Hamdan** ***et al.*** **(2014); Baccini** ***et al.*** **(2008) and Cummings** ***et al.*** **(2002).**

The high AGB of *Intsia bijuga* is mainly contributed by relatively high ρ (0.71 g cm^{-3}), high DBH (>40 cm) and high h (>21 m) compared to other species. Among all genera, *Mallotus* (ρ = 0.5 g cm^{-3}) has the lowest AGB (0.07 t tree^{-1}) whereas *Shorea* (ρ = 0.55 g cm^{-3}) has the highest AGB (0.83 t tree^{-1}) (Figure 4(b)). This suggests that *Intsia bijuga* tree species and *Shorea* genera have higher potentials for storing atmospheric carbon.

We further discriminated the mean AGB (t tree^{-1}) estimated using the allometric equation of Chave *et al.* (2005) into different groups based on tree DBH and species as follows: 10–15 cm, 15.01–20 cm, 20.01–25 cm….100.01–105 cm. The number of trees, number of tree species, mean AGB (t tree^{-1}) for each DBH category and the significance level describing the difference in mean AGB of different species at each species and DBH groups are shown in Table 4. By doing so we identified the tree species that showed the highest AGB for each DBH range (Figure 5).

The *Intsia bijuga* tree species demonstrated the highest AGB for the largest number (4) of the 5 cm DBH intervals, namely 35.01–40 cm, 80.01–85 cm, 85.01–90 cm and 100.01–105 cm. The difference in AGB among different tree species in these DBH groups is significant at $p < 0.001$ except for DBH group (100.01–105 cm). The *Koompassia malaccensis* tree species also demonstrated the highest AGB for 4 of the 5 cm DBH intervals, namely 20.01–25 cm, 40.01–45 cm, 45.01–50 cm, 130.01–135 cm. Again the difference in AGB among different tree species in these DBH groups is significant at $p < 0.001$ except for DBH group (130.01–135 cm). These tree species (i.e. *Intsia bijuga, Koompassia malaccensis* and *Shorea*) are categorized as threatened by the *International Union for Conservation of Nature* (IUCN, 2014).

The findings of this study can enhance our understanding of the importance of these tree species for carbon management and climate mitigation and thus promote further conservation efforts. Moreover, identifying tree species that have high AGB or carbon content is important to guide the local landscape authorities or urban planners in Malaysia and elsewhere in the wet tropics to decide which tree species should be planted during reforestation and in urban landscapes to mitigate climate change. This information is important for the Pasir Gudang municipal council in the southern region of Peninsular Malaysia in their efforts to reduce CO_2 from the atmosphere and

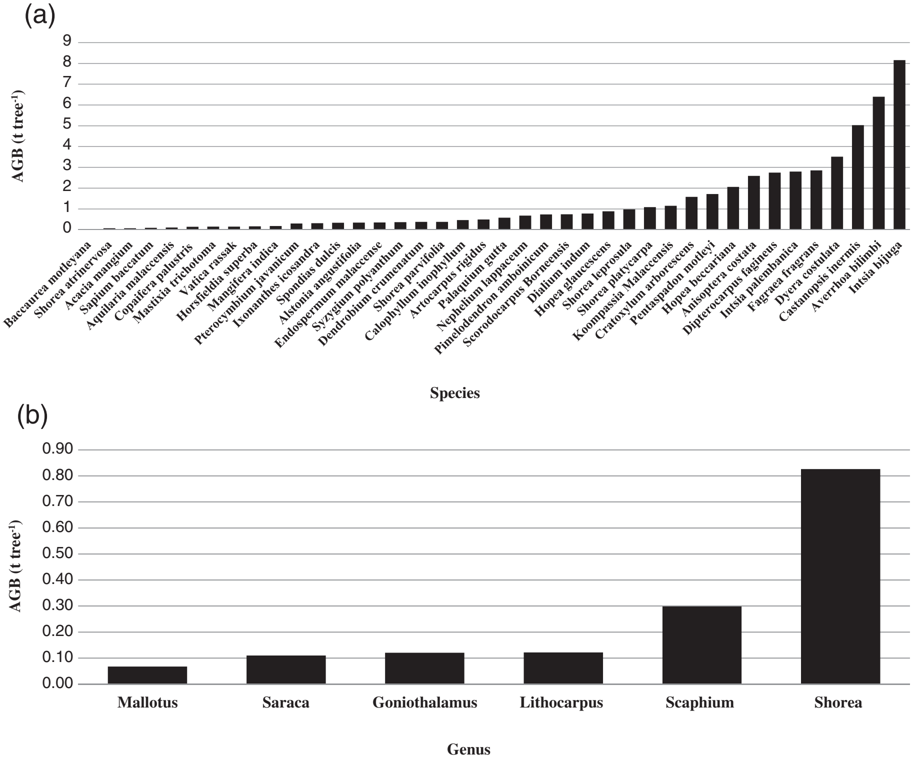

Figure 4. *The mean AGB (t tree^{-1}) of (a) species and (b) genera in the Royal Belum forest reserve.*
Source: **Graph prepared by Tan Kian Pang and Kasturi Devi Kanniah using data collected in the field.**

to mitigate any adverse impacts of climate change through planting of *Shorea* in the municipality, and other trees such as *Baccaurea ramiflora*, *Pentaspadon motley*, *Aglaia korthalsii*, *Syzygium cerinum* etc. along the road sides (Zanariah Kadir, head of Landscape Department, Pasir Gudang Municipality, pers. comm., Johor, Malaysia 20 April, 2015).

Relationships between AGB, PAI and fraction of canopy cover

We investigated the relationships between AGB and PAI, and fraction of canopy cover. The PAI ranged between 2.84 m^2 m^{-2} and 5.88 m^2 m^{-2} (mean 4.35 m^2 m^{-2}) and fraction of canopy cover ranged from 38.8 per cent to 96.1 per cent (mean 82.94 per cent); the lowest PAI and the lowest fraction of canopy cover were located in the secondary forests.

We found that the correlations of canopy parameters, i.e. PAI and fraction of canopy cover increases with AGB. The correlation of AGB and PAI (R^2 = 0.148) (Figure 6 (a)) is lower than the correlation of AGB and fraction of canopy cover (R^2 = 0.45) (Figure 6(b)). The distribution of PAI vs AGB shows considerable uncertainties due to the saturation of AGB to high PAI values at about 4 m^2 m^{-2}, while fraction of canopy cover vs AGB shows uncertainties at the level of about 80 per cent. The relationship between AGB and LAI was investigated by Zheng *et al*. (2007) in subtropical forest and it was found to be relatively strong (R^2 = 0.61), however, similar to our study, the

Table 4. The number of trees, tree species and the mean AGB for every 5 cm DBH intervals in the Royal Belum forest reserve.

DBH intervals (cm)	Number of trees	Number of tree species	Mean AGB ($t\ tree^{-1}$)
10.0–15.00	334	25	0.06*
15.01–20.00	220	24	0.12*
20.01–25.00	120	25	0.22*
25.01–30.00	77	20	0.37*
30.01–35.00	54	20	0.54*
35.01–40.00	31	17	0.78*
40.01–45.00	26	10	1.05*
45.01–50.00	19	12	1.46*
50.01–55.00	11	8	1.79*
55.01–60.00	13	9	2.24*
60.01–65.00	9	7	2.67*
65.01–70.00	8	6	3.21**
70.01–75.00	7	6	3.46
75.01–80.00	7	6	4.51*
80.01–85.00	4	4	5.28*
85.01–90.00	4	3	5.79*
90.01–95.00	2	2	6.94**
95.01–100.00	2	2	9.39
100.01–105.00	3	2	8.62
130.01–135.00	2	2	15.40

*$p < 0.001$; **$p < 0.05$. Note that there were no trees in the 105.01–130.00 range.
Source: Table prepared by Tan Kian Pang and Kasturi Devi Kanniah using data collected in the field.

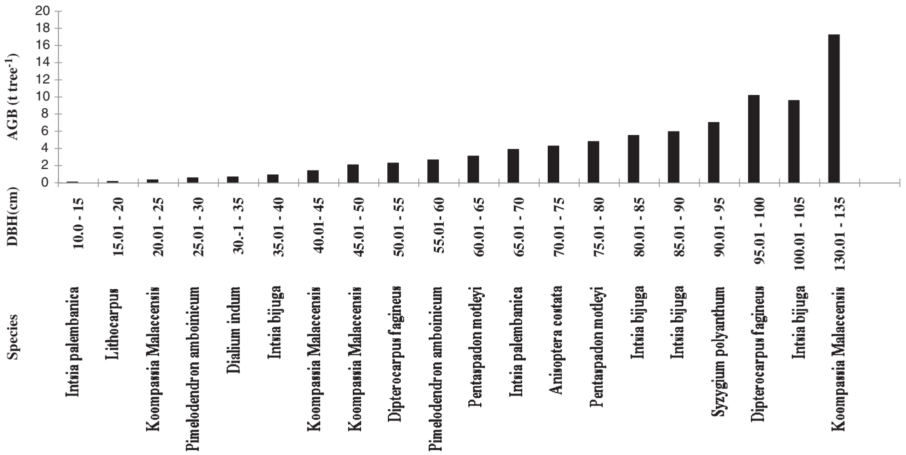

Figure 5. *The highest AGB ($t\ tree^{-1}$) estimated for each tree species in every 5 cm DBH interval category.*
Source: Graph prepared by Tan Kian Pang and Kasturi Devi Kanniah using data collected in the field.

AGB vs LAI has shown uncertainties due to the saturation of AGB to high LAI values above 4.5 $m^2\ m^{-2}$.

Disturbance and resource assessment for the forest

Scaling is widely used in many branches of natural science and some useful references are cited by Simini *et al.* (2010). The particular situation of interest to us is the relation between the number of trees and their size, as indicated by their DBH, and in this case scaling involves the assumption that the number of trees in a given area is related to the DBH by a simple power law. We used the data of Table 4 and plotted in Figure 7, the number of trees in the total study area against their DBH, excluding the largest few values of DBH for which the numbers of trees are very small. In the undisturbed forests a significantly large number of small trees (smaller DBH) compared to the large trees can be observed (Anfodillo *et al.*, 2013). The reason why the number of large trees in the undisturbed forest is small, is because high mortality in old trees creates large gaps that are then slowly refilled by small trees (Zeide, 2005). It is the consequence of resource competition by trees for a given site that leads to the different rate (fast or slow) of tree growth (Anfodillo *et al.*, 2013).

The curve in Figure 7 follows a negative power law $y = 15276\ x^{-2\text{-}32}$ with a value of $R^2 = 0.99$. In the model proposed by Simini *et al.* (2010) and Anfodillo *et al.* (2013) which is based on scaling theory, the number of trees varies with DBH according to a power law with a negative exponent of –(1 + 6H)/(1 + 2H) where H is a scaling parameter which takes the value H = 1 for tropical areas. This gives a theoretical value of the exponent of -7/3 or -2.33. Our experimental value of -2.32 is so close to the theoretical value that we can take it as demonstrating that the Royal Belum forest

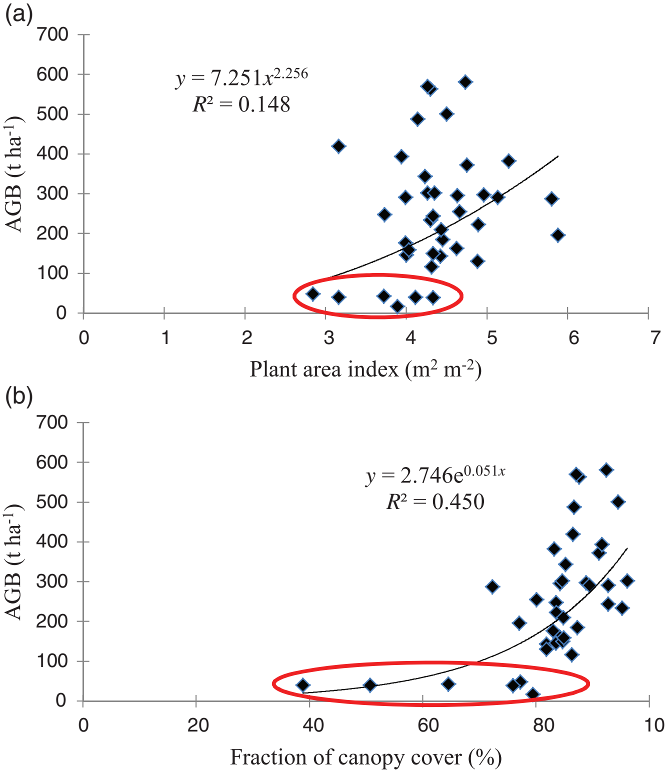

Figure 6. *The relationships of AGB (t ha^{-1}) and (a) plant area index (m^2 m^{-2}), (b) fraction of canopy cover (%) for 39 plots. The values of field plots in the secondary forest are shown inside the red oval. The values of field plots in the primary forest are shown outside the red oval.*

Source: Graph prepared by Tan Kian Pang using data collected in the field.

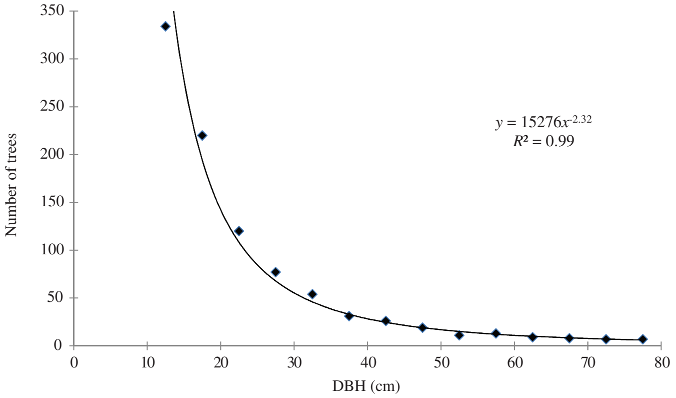

Figure 7. *Correlation of number of trees and DBH.*
Source: **Graph prepared by Tan Kian Pang and Kasturi Devi Kanniah using data collected in the field.**

maximizes resource use e.g. light energy, nutrients, etc. and thus can be classified as a 'true pristine forest'.

Conclusion

In this study, we derived AGB estimates for 39 plots in the Royal Belum forest reserve using allometric equations from Kato *et al.* (1978), Ketterings *et al.* (2001), Chave *et al.* (2005), and Basuki *et al.* (2009) and it was found that these allometric equations give no significantly different AGB estimates for trees with DBH ≤ 130 cm. However, the results obtained using the allometric equation of Kenzo *et al.* (2009) were only weakly correlated with the results from the other four allometric equations. We found a moderately good correlation of the AGB with the fractional canopy cover ($R^2 = 0.45$), but a weak correlation of AGB with PAI ($R^2 = 0.148$). We also found that the AGB of *Intsia bijuga, Koompassia malaccensis* and *Shorea* were higher than the other species in the Royal Belum forest reserve. This suggests that these species have a higher potential than other tree species to store carbon or remove CO_2 from the atmosphere. Our results also showed the Royal Belum forest reserve is a pristine forest based on a model proposed by Simini *et al.* (2010) and Anfodillo *et al.* (2013), in which the number of trees varies with DBH according to a power law with a negative exponent of -2.32. The AGB values of the Royal Belum forest reserve are the highest compared to some studies of other areas in Malaysia and some other tropical forests. The mean AGB value of the Royal Belum forest reserve (293.16 t ha^{-1}) is comparable to other primary forests, and higher than secondary forests or mangrove forest areas in Malaysia. The total AGB of dipterocarp forests in Peninsular Malaysia was estimated using satellite images and found to be about 1.82 billion tonnes (Omar *et al.*, 2015). This implies that the Royal Belum forest reserve which is one the oldest primary forests, older than the forests in the Amazon and the Congo (MNS, 2005), is an important resource for storing carbon.

Our results could be used to estimate, by extrapolation, the total carbon stock in the whole Royal Belum forest. However, in the analysis of our data we excluded one very large tree with DBH 228.9 cm and height 49.46 m in our sample plot 10. If one goes through the whole forest, one would expect to find other examples of such trees—however we are unable to ascertain exactly how many of such trees exist. Clearly, such very large trees are rather uncommon given that we had only encountered one such specimen amongst the 954 trees (having DBH larger than 10 cm) in our 39 sample plots. Had we chosen our 39 plots differently, we may not even have found any. We have no evidence regarding the average density (number of trees per hectare) of these trees in the forest. As such, we could not take them into account in estimating the total AGB, and therefore, by extension, the total carbon content of the whole forest. These very large trees will make an unknown extra contribution to the total carbon content of the forest.

In a future study, we suggest using terrestrial laser scanning (TLS) which is one of the rapidly growing technologies for fast and reliable characterization of a 3D forest through point cloud data acquisition. TLS can obtain biophysical information such as stem and canopy components of trees rather easily and rapidly compared to the traditional field survey method (Kankare *et al.*, 2013). The findings of this study constitute potentially valuable information on the forests of Malaysia which should be reported to the United Nations Framework Convention on Climate Change and REDD++ programme to aid them in their work on climate change mitigation.

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