



## Estimation of aboveground biomass in logged and primary lowland rainforests using 3-D photogrammetric analysis

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### Abstract

We estimated the total aboveground tree biomass (TAGB) in an old-growth primary forest and in a regenerating forest that had been selectively logged in 1958, both within the tropical rainforest of the Pasoh Forest Reserve in Peninsular Malaysia. This was achieved by comparing aerial photographs with data obtained previously from destructive sampling in the same area. Aerial photographs were taken above the primary and logged forest plots in 1997. The heights of the canopy-forming trees were estimated in both plots by means of aerial triangulation and were regressed against the diameter at breast height (DBH) of the corresponding trees measured during ground surveys. The resulting allometric relationship between tree height and DBH let us estimate TAGB: in the primary forest, TAGB was 310 Mg ha<sup>-1</sup>, which was ca. 10–12% smaller than the value estimated by means of destructive sampling conducted in the 1970s. The estimated TAGB of the logged forest was 274 Mg ha<sup>-1</sup>, which was significantly smaller than that of the primary forest ( $P < 0.05$ ). We also measured canopy surface height in a 2.5 m grid system. We found that the mean canopy surface height (MCH) in every 20 m × 20 m subplot (0.04 ha) was significantly ( $P < 0.0001$ ) correlated with TAGB for that subplot. This suggests that the spatial variation of TAGB can be estimated using MCH values obtained from such a grid system, and that biomass levels can potentially be estimated by means of satellite remote sensing on larger scales, even for very dense tropical forests. We also found that digital reflectance values from Landsat Thematic Mapper (TM) images differed significantly between the logged and primary forests, and hypothesize that these differences relate to structural differences in the canopy surface. However, TAGB in both plots was poorly correlated with the Landsat reflectance values, suggesting the necessity of using an active remote-sensing sensor or a laser profiling system that can quantify changes in the forest's vertical structure or volume to estimate biomass and its variation in dense evergreen forests.

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## 1. Introduction

Estimating forest biomass is an important task when assessing carbon stocks and the amount of carbon sequestration in tropical forests, and much effort has been devoted to developing innovative methods for predicting the total aboveground biomass (TAGB) in forest ecosystems or to improving existing methods (Ogawa et al., 1965; Kato et al., 1978; Yoneda, 1982; Anderson et al., 1983; Proctor et al., 1983; Yoneda et al., 1994). Monitoring and precise mapping of residual TAGB after logging operations are also important tasks for predicting the impact of logging and for facilitating proper management of tropical forests, in which deforestation is proceeding faster than in any other forest ecosystem (FAO, 1996, 1997). However, most estimations of biomass have been restricted to local patches of tropical forest, primarily because of the labor-intensive field measurements that are required, such as determining tree heights and the diameter at breast height (DBH) of the main stems, both of which are required for predicting tree biomass. Accurate estimations of TAGB require measurements of the actual tree dimensions by means of destructive sampling (Ogawa et al., 1965; Kato et al., 1978).

In the Pasoh Forest Reserve, where the present study was conducted, all trees within a 100 m × 20 m study plot set in the primary forest had been previously harvested in order to estimate the TAGB and carbon budget of this tropical rainforest (Kato et al., 1978). Allometric relationships between tree biomass and the combination of tree height and DBH were obtained from the felled trees from within this study plot. However, to extrapolate these results over a broader area of the forest and to estimate TAGB, researchers must measure the diameters of all trees in the target area. Furthermore, the forest structure and species composition of tropical forests are both known to be spatially heterogeneous (Ricklefs, 1977; Denslow, 1980; Pickett, 1983; Yoneda et al., 1994; Richards, 1996; Terborgh and Mathews, 1999), so information obtained from localized destructive sampling cannot be readily applied to other disturbed areas that may have different structures from those of virgin forests. To overcome this problem, satellite images have often been used to predict biomass at larger landscape scales (Luckman et al., 1998; Boyd et al., 1999), but the

accuracy of these estimates remain unknown, particularly when the forests are locally heterogeneous as a result of different logging histories or other factors (Sader et al., 1989; Kimes et al., 1998, Foody and Boyd, 2002).

Considering the rapid rate of deforestation in the tropics, methods are urgently needed to fill the gap between satellite image analyses, which are fast but potentially inaccurate, and ground surveys, which are accurate but extremely time-consuming. In the present study, we examined the feasibility of using aerial photographs to estimate TAGB in a lowland tropical rainforest and investigated whether we could detect the spatial heterogeneity of TAGB in primary and selectively logged forests. We also measured the mean canopy height (MCH) in the cells of a grid system that covered the target area (the study plots) and examined how precisely the TAGB value per unit area (subplot) could be estimated by using the MCH of the subplot as the predictive variable without knowing the diameters of the individual trees. Third, we examined the feasibility of using satellite images (Landsat TM) to detect differences in TAGB between the logged and primary forests. The primary objective of this investigation was to explore the possibility of replacing costly and time-consuming ground surveys with stereoscopic analysis of aerial photographs, and perhaps even to propose the use of satellite remote sensing if this approach could be demonstrated to be sufficiently accurate.

## 2. Materials and methods

### 2.1. Study area

The present study was conducted in an old-growth, lowland dipterocarp forest within the Pasoh Forest Reserve (lat. 2°59'N, long. 102°18'E), which is located in the state of Negeri Sembilan, about 70 km southeast of Kuala Lumpur, Malaysia. The mean annual rainfall from 1974 to 1992 at Pasoh-Dua (lat. 2°56'N, long. 102°18'E), 6 km south of the reserve, was 1842 mm, with distinct rainfall peaks in April–May and November–December (based on data provided by the Malaysian Meteorological Service). The soil is of the Bungor–Malacca Association type (based on data provided by the Malaysian Soil Science

Division), which develops mainly from shale, granite, and fluvialite granitic alluvium parent materials (Allbrook, 1973). The topography consists mainly of flat alluvial areas, with smaller expanses of swales, riverine areas, and gently rolling hills.

The overall vegetation type in the reserve is lowland dipterocarp forest, which is characterized by a high proportion of species in the Dipterocarpaceae (Symington, 1943; Wyatt-Smith, 1961, 1964). On the basis of floristic evidence, the primary forest in the study area was generally homogeneous, with no evidence of major disturbance, and appeared to be representative of the lowland forest of the south-central Malay Peninsula (Kochummen et al., 1990; Manokaran and LaFrankie, 1990). Lowland dipterocarp forest is one of the most species-rich communities in the world, with more than 200 tree species per hectare. In contrast, the southern and eastern edges of the reserve had been selectively logged from the mid-1950s until the early 1970s, and at the time of the study, represented regenerating forest.

## 2.2. Tree censuses in the study plots

Two study plots were established within the reserve: a 50 ha plot (1000 m × 500 m) lay in the primary forest toward the center of the reserve, and a 6 ha plot (300 m × 200 m) lay within an area of logged forest in which selective logging had been practiced in 1958 in accordance with the Malayan (later Malaysian) uniform system (MUS) (Wyatt-Smith, 1963; Thang, 1987, 1997). A previous investigation of the canopy and forest structure in the primary and logged forests (Okuda et al., 2003) revealed that the average stem density and basal area did not differ significantly ( $F_{1,222} = 2.26$ ,  $P = 0.067$ , ANOVA) between the two forests. However, the canopy height differed significantly between the two areas ( $F_{1,90400} = 651.90$ ,  $P < 0.0001$ , ANOVA), averaging 27.4 m in the primary forest and 24.8 m in the logged forest. The stand structure also differed between the two forest areas: the stem density (trees ha<sup>-1</sup>) of small- to medium-sized trees (10–30 cm in DBH) was significantly higher ( $F_{1,222} = 41.25$ ,  $P < 0.0001$ , ANOVA) in the logged forest than in the primary forest, although the mean stem density and basal area across all tree sizes did not differ between the two forests. The canopy structure in the logged

forest was homogeneous, whereas that in the primary forest was highly complex, with a higher density of emergent and tall canopy trees. These trends for stand structure and canopy height were observed throughout the logged forest in the Reserve: Supardi (1999) found a higher density of medium-sized trees (10–30 cm in DBH) in the logged forest (sixteen 1 ha plots) than in the primary forest in an analysis of stem density in study plots elsewhere in the Reserve. Similarly, Manokaran (1998) studied stem densities elsewhere in the Pasoh Forest Reserve (four 2 ha plots in primary forest and one 2 ha plot in logged forest) and found that the stem density of trees 10–30 cm in DBH was higher in the logged forest than in the primary forest. This difference was particularly apparent for the Dipterocarpaceae, a tree species group favored for timber production, which showed a higher density of these medium-sized trees. However, Manokaran stated that mean basal area across all classes did not differ distinctly. He also showed that mean tree height in the canopy and emergent layers was much lower in the logged forest than in the primary forests.

Because selective logging removes large timber trees (the lower cutting limit is typically 45–50 cm in DBH) during the operation, trees are generally absent in the emergent and canopy layers (40–50 m or greater in height) in the logged sites, and the forest physiognomy (including the canopy structure) in the regenerating forest becomes monotonous (Okuda et al., 2003). Therefore, although the sample plot in the logged site in the present study was smaller than the plot in the primary forest (6 ha versus 50 ha), we considered our study plot in the logged forest to be representative of the overall structural conditions in the logged forest; these conditions, which resulted from selective harvesting of large trees under the MUS logging regime, are common throughout the reserve, irrespective of topography. Although the maximum slopes were greater in the logged forest, mean slopes were comparable.

The tree census in the logged forest plot was conducted between October 1997 and February 1999 following the methods of Manokaran et al. (1990). The same approach had been previously used by the Forest Research Institute Malaysia and the Smithsonian Institution in 1985 to establish and census the 50 ha plot in the primary forest. In both plots, all woody plants  $\geq 1$  cm in DBH were identified, tagged, and

measured for DBH, and their positions were mapped to the nearest 10 cm. The census of the primary forest that we used was based on the second 5-year re-census of the forest, which occurred between November 1995 and November 1997 (Manokaran et al., 1999).

As a reference for TAGB estimation, we also analyzed the tree census data obtained in another primary forest plot (6 ha) established south of the current study's old-growth forest in the early 1970s under the International Biological Program (hereafter referred to as the IBP plot), in which all trees ( $\geq 5$  cm in DBH) have been measured and mapped since the early 1970s; the species composition, stand structure, and other vegetational aspects of this plot have also been monitored (Manokaran, 1998; K. Niiyama et al., unpublished data, Forestry and Forest Product Research Institute, Japan). Destructive sampling for biomass estimation was conducted inside this plot (Kato et al., 1978).

### 2.3. Aerial photographs of the canopy's surface structure

Aerial photographs of the center of the Pasoh Forest Reserve that covered both plots were taken at a 1:6000 scale in February 1997. To produce a photogrammetric map, four 1 m  $\times$  1 m markers were set in place before the aerial photography was conducted to serve as ground control points. Two markers were hung between canopy trees at the northern corners of the 50 ha plot, and the other two markers were set on the ground outside the forest, in an area that had been converted into an oil palm plantation in the early 1970s. The visibility of all four markers from the air was confirmed before the aerial photographs were taken. The 6 ha plot in the logged forest was established beneath the flight lines that connected the markers outside and inside the forest. The positions of these markers were surveyed using GPS receivers, and traverses were performed with an Electronic Distance Measurement (EDM) instrument (manufactured by TOPCON Co., Tokyo Japan), which measures distances using electromagnetic waves. In addition to the four ground control points, four reference points (marked using PVC pipe) were placed inside each plot to permit calibration of elevations and coordinates. The final coordinates and elevations were linked with the Malaysian Rectified Skew Ortho-

morphic System and topographical heights obtained from this system.

Aerial triangulation based on the aerial photographs and ground control points was used to establish the necessary minor photographic control points for stereoscopic digitizing. A digital elevation model of the canopy surface (CDEM) was developed using an analytical stereo plotter. The measurement procedure for canopy heights based on 3-D triangulation has been detailed in a previous paper (Okuda et al., 2003).

The crowns of the canopy trees in the aerial photographs were mapped and delineated in both plots by using stereoscopes to measure the highest visible points of the individual crowns. Trees with large crown sizes ( $\geq 300$  m<sup>2</sup>, about 20 m in diameter) were more abundant in the primary forest than in the logged forest (Okuda et al., 2003), and such large and tall trees sometimes concealed smaller understory trees. In contrast, the canopy surface of the logged forest consisted of many trees with small crowns ( $\leq 100$  m<sup>2</sup>, about 11 m in diameter), most of which were visible in the aerial photographs. Thus, the proportion of the trees sampled for the regression analysis of DBH against tree height was smaller in the primary forest than in the logged forest.

To match the trees observed in the aerial photos with trees measured in the censuses conducted in the primary and logged forests, we identified the highest point in each crown and projected this to the ground. We then selected the census tree with the largest DBH within a 4 m radius from that point. On the basis of these procedures, simple regression lines were fitted to the DBH and tree height data:

$$\frac{1}{H} = \frac{1}{(aD)} + \frac{1}{H_{\max}}, \quad (1)$$

where  $H$  is the tree's height (m),  $D$  is its DBH (cm),  $H_{\max}$  is the maximum tree height (m) observed in the plot, and  $a$  is a regression coefficient (Ogawa et al., 1965; Kato et al., 1978). Kato et al. (1978) suggested a coefficient of 2.0. The  $H$ - $D$  relationship was exponential, with an asymptote at  $H_{\max}$ , and we re-examined the precise shape of the relationship in the present study to confirm the validity of Kato et al.'s regression coefficient. However, we accepted the equations of Kato et al. (1978) for calculating the weights (kg) of

the main stem ( $W_s$ ), branches ( $W_b$ ), and leaves ( $W_l$ ):

$$W_s = 0.0313 (D^2H)^{0.9733} \tag{2}$$

$$W_b = 0.039 (D^2H)^{1.041} \tag{3}$$

$$\frac{1}{W_l} = \frac{1}{(0.124 W_s^{0.794})} + \frac{1}{125} \tag{4}$$

On the basis of these equations, the total aboveground biomass (TAGB) was calculated as

$$\text{TAGB} = W_s + W_b + W_l \tag{5}$$

by using data from all trees with DBH  $\geq 5$  cm. In our preliminary study on TAGB in the primary forest plot, the relative error introduced by ignoring trees with a DBH of 1–5 cm was  $<1.5\%$ .

The digitization of canopy height was conducted by using a grid pattern with 2.5 m intervals. The accuracy of the height measurements was better than 0.5 m for well-defined and clear surface objects (e.g., the canopy tower near the study area, the 1 m  $\times$  1 m markers, and the roads or trails in the oil palm plantation). The grid data for the elevations of points on the ground were interpolated at 2.5 m intervals to match the array in the CDEM's sub-grid system. Canopy height was then obtained by subtracting the ground elevations from the CDEM height for every 2.5 m interval. The MCH was obtained for 20 m  $\times$  20 m subplots and was regressed against TAGB for each individual subplot.

To investigate whether satellite images could detect variations in canopy structure and vertical height related to logging history, we analyzed the reflectance values in Landsat TM data acquired in 1996 for the Pasoh Forest Reserve in an attempt to detect

differences in TAGB between the primary and logged forests by means of satellite remote sensing. The reflectance value in each of six bands (Table 1), expressed as digital numbers (DN) at an 8-bit quantization level, were extracted from every 20 m  $\times$  20 m subplot within the primary and logged forest plots. Each reflectance value for a subplot was assigned coordinates so that it could be matched with the corresponding canopy height and TAGB data for the subplot, and the relationships between canopy height and reflectance and between TAGB and reflectance were analyzed.

Prior to the extraction of reflectance values for each sub-plot, the TM image was geometrically corrected. In this process, the image was first geometrically transformed to fit the corresponding area surveyed on the ground, and then re-sampling was conducted to assign the reflectance values from the raw image data to the geometrically corrected image. In this transformation process, the image-to-map registration technique (Jensen, 2000; Richards and Jia, 1999) was employed using a second-degree polynomial transformation. Any point of interest  $i$  in the image and its corresponding map coordinates are linked in the transformation function by:

$$X_i = a_1x_i^2 + 2a_2x_i + a_3 \tag{6}$$

$$Y_i = b_1y_i^2 + 2b_2y_i + b_3 \tag{7}$$

where  $X$  and  $Y$  are the map coordinates for point  $i$ ;  $x$  and  $y$  are the pixel coordinates of point  $i$  in the image; and  $a_1$ ,  $a_2$ ,  $a_3$ ,  $b_1$ ,  $b_2$ , and  $b_3$  are coefficients of the transformation. A total of 20 ground control points, which were easily identifiable permanent features

Table 1  
Comparison of mean ( $\pm$ standard error) Landsat TM digital reflectance values (DRV) for the primary and logged forest plots

Band (wavelength, $\mu\text{m}$ )	Digital reflectance value				$F_{1,1398}$	$P$
	Primary forest		Logged forest			
	Mean	S.E.	Mean	S.E.		
1 (0.45–0.52)	127.37	0.047	127.67	0.142	4.18	0.0412
2 (0.52–0.60)	74.24	0.027	74.86	0.103	51.61	$< 0.0001$
3 (0.63–0.69)	19.24	0.026	19.55	0.070	45.88	$< 0.0001$
4 (0.75–0.90)	67.81	0.124	76.44	0.650	414.91	$< 0.0001$
5 (1.55–1.75)	43.49	0.083	46.28	0.389	103.68	$< 0.0001$
7 (2.08–2.35)	13.02	0.034	13.36	0.126	9.98	0.0016

The DRV were extracted from the Landsat TM image acquired in 1996, and were averaged within each of the plots ( $n = 1250$  for the primary forest and  $n = 150$  for the logged forest).  $P$ -values were obtained by means of ANOVA.

found in both the Landsat image and the corresponding part of the topographic map and which were well distributed within the area, were used in the transformation. The geometric transformation accuracy we achieved equaled  $\pm 0.1$  of a pixel (i.e.,  $\pm 3$  m at the 30 m resolution of the TM image).

The second step in the geometric correction is the re-sampling process. A 20 m grid was used for interpolation of the reflectance values in the final pixel of the geometrically transformed image; thus, the final pixel size in the geometrically corrected image was 20 m. A nearest-neighbour re-sampling technique was used in the re-sampling process to ensure that the reflectance would not change dramatically from the value in the raw image data. All the steps in the geometric correction were performed using the image processing system software (Vision Tech Inc., Tsukuba, Japan).

Differences in TAGB between study plots were analyzed by means of ANOVA. For this analysis, each of the study plots was subdivided into 20 m  $\times$  20 m subplots, and the TAGB obtained in each subplot (0.04 ha) was used. We found that the sample had a normal distribution, and thus were able to use ANOVA for our statistical analysis. The mean TAGB value per plot was converted into a value per hectare to facilitate comparisons with the results of other studies. Simple regression analysis was conducted to test the relationship between tree height and DBH and the relationship between MCH and TAGB. The significance of the

difference in regression slopes between the primary and logged forests was tested by means of ANCOVA. All statistical tests were conducted with the stat view software (version 5.0, SAS Institute Inc., Cary, NC, USA).

### 3. Results and discussion

#### 3.1. Allometric relationships between tree height and diameter ( $H$ – $D$ relationships)

Tree heights ( $H$ , in m) derived from the stereoscopic analysis of the tree crowns were matched with the DBH ( $D$ , in cm) of the corresponding trees from the tree census. Regression Eqs. (8) and (9) (based on equation 1) describe the resulting allometric relationships for each study plot:

$$\frac{1}{H} = \frac{1}{(1.5D)} + \frac{1}{61} \quad \text{primary forest,} \quad (8)$$

$$\frac{1}{H} = \frac{1}{(2.2D)} + \frac{1}{47} \quad \text{logged forest.} \quad (9)$$

The initial slope of the  $H$ – $D$  curve ( $D \leq 30$  cm) was greater in the logged forest (Fig. 1), but ANCOVA revealed that there was no significant difference between the initial slopes for the two forest types.

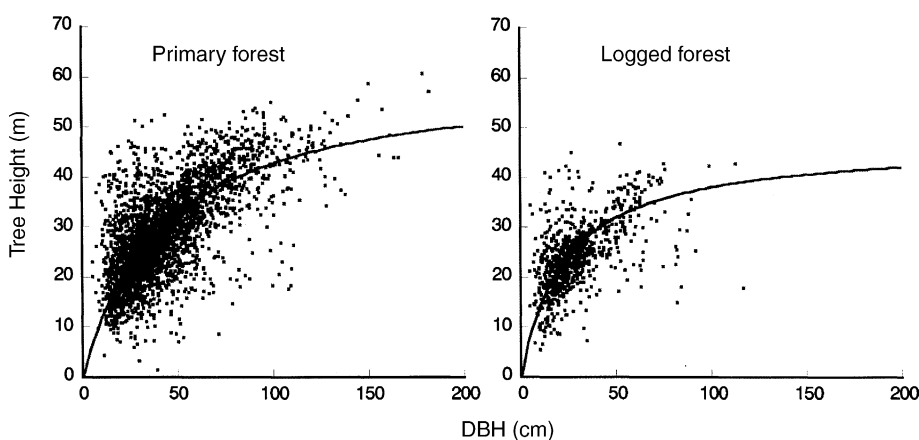


Fig. 1. Allometric relationships between DBH ( $D$ ) and tree height ( $H$ ) in the primary ( $n = 3224$ ) and logged ( $n = 819$ ) forests. Regression equations for these relationships (Eqs. (8) and (9), respectively) are presented in the text. Simple regression analysis revealed that the relationships between  $1/D$  and  $1/H$  were significant for both forests ( $r^2 = 0.736$ ,  $P < 0.0001$  in the primary forest;  $r^2 = 0.703$ ,  $P < 0.0001$  in the logged forest). The standard error for the parameter (regression coefficient,  $1/D$ ) was 0.007 for the primary forest and 0.011 for the logged forest.

In contrast, ANCOVA showed a significant  $\ln(D) \times$  forest type (primary versus logged) interaction, and that the overall slope of the regression was significantly greater in the primary forest ( $F_{1,4040} = 17.88$ ,  $P < 0.0001$ ). This was primarily because the curve fitting (Fig. 1) was strongly influenced by differences in the density of large trees and in the maximum tree height ( $H_{\max}$ ) that served as the asymptote for each curve. As mentioned earlier, the lower density of large trees and the lower MCH in the logged forest resulted from removal of the largest trees by selective logging. This reduced MCH, and the forest has not yet recovered completely because the density of smaller canopy-forming trees was significantly higher in the logged forest (Okuda et al., 2003). Growth of the canopy-forming trees may have been suppressed by their high density. The canopy structure in the logged forest was distinctly more homogeneous than in the primary forest, and showed significantly less variation in average canopy height (Okuda et al., 2003). Therefore, the very high density of canopy candidates (DBH, 30–40 cm) coupled with the low frequency of gap formation (after the gaps generated through harvesting were colonized) appear to have impeded the development of complexity in the logged forest's structure. This conclusion suggests that the net primary production (NPP) of the forest may depend on the forest's structure and maturity. The forest's logging history and the logging intensity, both of which are likely to influence the  $H$ – $D$  relationship of the surviving trees, must be considered in terms of its effects on TAGB.

### 3.2. Comparison of TAGB between the primary and logged forests

On the basis of the  $H$ – $D$  allometric relationships derived in our study (Eqs. (8) and (9)), we estimated TAGB as  $310.3 \text{ Mg ha}^{-1}$  in the primary forest and  $274.4 \text{ Mg ha}^{-1}$  in the logged forest; this difference was significant ( $F_{1,1398} = 5.56$ ,  $P = 0.019$ , ANOVA). These values were ca. 10% to 12% smaller than those estimated by Kato et al. (1978), who used a coefficient of 2.0 irrespective of logging history; using their coefficient would have produced TAGB values of  $352.8$  and  $300.7 \text{ Mg ha}^{-1}$ , respectively. There were always significant differences in TAGB ( $P < 0.001$ , ANOVA) between the two forests regardless of the

allometric  $H$ – $D$  equation (1, 8, 9) used. Moreover, a more strongly significant difference ( $F_{1,1398} = 9.94$ ,  $P = 0.0017$ ) was obtained when Eq. (1) was used to estimate TAGB for both forests than when Eqs. (8) and (9) were used to account for differences in forest type. These results are probably due to the greater height increment as a function of DBH (Fig. 1) for the smaller trees ( $D \leq 30$  cm) in the logged forest being offset by the lower abundance of large trees ( $D \geq 70$  cm) in that forest.

Although the size of the sample plot in the logged forests was smaller than that of the plot in primary forests, the relative absence of large trees (e.g.,  $>50$  cm in DBH and  $>40$  m in height) is commonly seen on logged sites, both in our study area (the Pasoh Forest Reserve) and elsewhere across Peninsular Malaysia (Manokaran, 1998). Therefore, as mentioned earlier, we believe that the size of the sample plot in the logged forest is sufficiently large to represent the variation in structure and stand volume of the logged forest and to permit a comparison with the primary forests. Furthermore, the species–area curve in the 6 ha plot of logged forest was nearly saturated (Okuda et al., unpublished), which implies that most of the common timber species (e.g., the Dipterocarpaceae) that account for the majority of the total biomass will be included within a plot of this size. Further variation in structure and biomass are unlikely above this plot size in the logged forest.

Therefore, we believe that the significant difference in mean TAGB values between the two forest types arose primarily from their different densities of large trees and was not an artifact of plot size. Although the overall mean stem density for all tree sizes ( $\geq 1$  cm in DBH) did not differ between the two forests, the density of large trees ( $\geq 70$  cm in DBH) was significantly greater ( $P < 0.05$ ) in the primary forest (Okuda et al., 2003). TAGB depended strongly on the density of these large trees, because even a single large tree greatly increased TAGB for a given area. The canopy was generally taller on slopes than on flat alluvial topography, which had poor drainage (Okuda et al., 2004). The distribution pattern of the large trees with respect to DBH generally followed this trend; that is, larger trees were more common on slopes. Accordingly, TAGB varied greatly within the primary forest plot because of the wide range of slopes, and ranged from  $215.8$  to  $401.6 \text{ Mg ha}^{-1}$  (Fig. 2). Yoneda

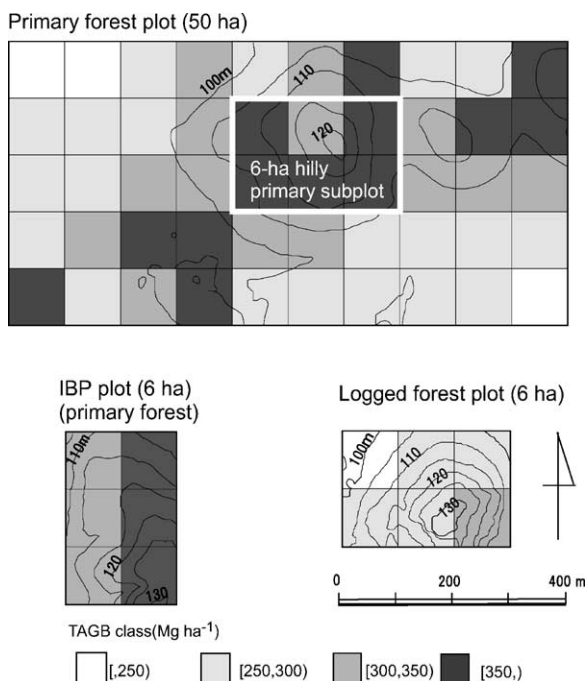


Fig. 2. Distribution of TAGB (Mg ha<sup>-1</sup>) in the primary (50 ha) and logged (6 ha) forests. The TAGB distribution for the International Biological Program plot (IBP plot, 6 ha), located in another area of primary forest in the Pasoh Forest Reserve, is provided as a reference. In the 50 ha primary forest, TAGB averaged 310.3 Mg ha<sup>-1</sup> and ranged from 215.8 to 401.6 Mg ha<sup>-1</sup>. In the 6 ha primary forest (IBP plot), TAGB averaged 357.3 Mg ha<sup>-1</sup> and ranged from 322.9 to 390.3 Mg ha<sup>-1</sup>. In the 6 ha logged forest, TAGB averaged 274.4 Mg ha<sup>-1</sup> and ranged from 210.5 to 329.8 Mg ha<sup>-1</sup>. In the hilly subplot of the 50 ha primary forest (the 6 ha area surrounded by the solid white lines), TAGB averaged 364.8 Mg ha<sup>-1</sup> and ranged from 301.7 to 401.6 Mg ha<sup>-1</sup>.

et al. (1994) also reported that TAGB almost doubled between sites with the lowest and highest elevations in a Sumatran rainforest. Therefore, topographic variations in TAGB must be considered when one is examining carbon sequestration by tropical forests.

Such spatial heterogeneities in TAGB might have caused the moderate difference in TAGB (which was significant, but only at  $P < 0.05$ ) between the two forests; that is, if we sampled only hill or slope areas from the primary forest then the differences in TAGB between the two forests would be larger, because about 70% of the primary forest plot consisted of flat alluvial topography (the rest was hill or slope) versus 90% for the logged forest plot. To test this hypothesis, we selected 6 ha hilly subplots within the primary

forest plot (hereafter, '6 ha hilly primary subplot'; the area bordered by solid white lines in Fig. 2) and found that the TAGB value for the area was 364.8 Mg ha<sup>-1</sup>, which was significantly higher than that in the logged forest plot ( $F_{1,1398} = 20.25$ ,  $P = 0.0001$ ; ANOVA).

Although the IBP plot was at the crest of a northwest-sloping hill, its topography was similar to that of the logged plot and that of the 6 ha hilly primary subplot (Fig. 2). On the basis of the 1998 DBH data from this plot and the allometric  $H-D$  relationships from the present study, we estimated that the IBP plot's TAGB was 357.3 Mg ha<sup>-1</sup>, which was also significantly higher than that in the logged forest plot ( $F_{1,2988} = 13.156$ ,  $P < 0.0001$ ; ANOVA). The topography and soil type in the logged forest plot resembled those in the hilly areas of the 50 ha primary forest and those of the entire IBP plot. Thus, accounting for the effects of topography on TAGB estimations confirms that TAGB is generally higher in the primary forest (Fig. 2) than in the logged forest after 40 years of post-harvest regeneration. A post-logging tree census in a forest compartment near the Pasoh Forest Reserve revealed that basal area (m<sup>2</sup>/ha) had been reduced by 30% from the pre-logging status (S. Nishimura, National Institute for Environmental Studies, unpublished data). Although the logging regime used in the 1950s was more moderate than the present Sustainable Management System (Manokaran, 1998), the results of the present study suggest that the TAGB has not yet fully recovered, even 40 years after selective logging conducted under the MUS.

### 3.3. Estimation of TAGB from canopy heights

TAGB was significantly correlated with MCH in both forests ( $r^2 = 0.326$  and  $P < 0.001$  for primary forest;  $r^2 = 0.439$  and  $P < 0.001$  for logged forest; Fig. 3). ANCOVA revealed no interaction between forest type (primary versus logged) and the effect of MCH on TAGB ( $F_{1,1398} = 3.343$ ,  $P > 0.05$ ). This suggests that there was no significant difference in the slope of the regression line between the two forests, and that forest type alone caused the significant difference.

In addition to these statistical tests, we randomly sampled MCH in 20 m × 20 m subplots in order to examine the accuracy of the biomass estimation model as a function of canopy height (regression equations shown in Fig. 3); we used 10%, 20%, and 50% of all



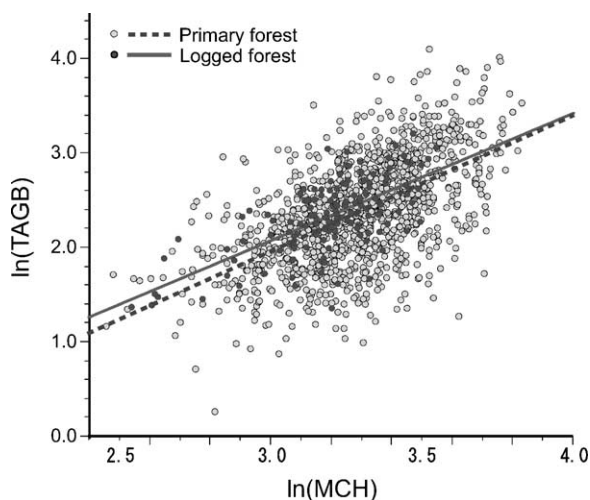


Fig. 3. Relationship between mean canopy height (MCH) and TAGB in the primary and logged forests. MCH was calculated from data at 64 points in a 20 m  $\times$  20 m subplot whose canopy height was measured by means of aerial triangulation using a 2.5 m grid system in the primary and logged forest plots. The regression equations are:  $\ln(\text{TAGB}) = -2.372 + 1.441 \ln(\text{MCH})$ ,  $r^2 = 0.326$ , for the primary forest; and  $\ln(\text{TAGB}) = -1.983 + 1.348 \ln(\text{MCH})$ ,  $r^2 = 0.439$ , for the logged forest. The regression correlations in both plots were significant at  $P < 0.0001$ .

subplots, and calculated the 'expected value' of TAGB based on the MCH–TAGB model for each of these selected subplots. We found that the mean expected value did not differ significantly ( $P > 0.05$ , ANOVA) from the mean TAGB calculated from the DBH of all trees recorded in each subplot at any level of random sampling (10%, 20%, and 50% of the total plots).

These findings suggest that TAGB can be estimated from canopy height data (represented by MCH in the present study), regardless of the forest type, if canopy heights are systematically measured by means of stereoscopic analysis of aerial photographs. This approach eliminates the need for labor-intensive ground surveys to measure DBH. Furthermore, canopy heights can be measured more efficiently at fixed horizontal intervals by using aerial triangulation than by measuring individual crown heights, which requires identification of the edges of individual crowns. However, as indicated in our discussion of the coefficient proposed by Kato et al. (1978), estimates of TAGB should be based on locally derived  $H$ – $D$  allometric relationship rather than on general values from the literature.

The significant relationship between MCH and TAGB that is evident in the results of our analysis of data from the aerial photographs suggests that it might be possible to scale up this technique to permit the use of satellite remote sensing data. That is, if local variations in TAGB could be detected from satellite images that provide structural information on the vegetation surface, it would become possible to reduce the dependence on large-scale aerial photography and on labor-intensive measurements of the DBH and height of individual trees (Botkin et al., 1984).

To test this hypothesis, we compared the Landsat TM reflectance values for Bands 1, 2, 3, 4, 5, and 7 between the two forests and found that the average reflectance values differed significantly between the two forest types ( $P < 0.001$  in all cases, ANOVA; Table 1). We suspect that these differences arose primarily from differences between the two forests in the canopy surface texture (i.e., structure) or canopy height. However, the significant differences in the reflectance values may also have resulted in part from the large number of samples (d.f. = 1398). When the reflectance values for these bands were randomly chosen from about 20% of the total number of samples, the differences became non-significant ( $P > 0.05$ , ANOVA), except for Bands 2, 4, and 5 ( $F_{1,273} = 12.06$ , 165.43, and 41.41, respectively,  $P < 0.001$  for all three bands). Furthermore, although the average canopy height was negatively correlated with the reflectance value in Bands 4 and 5 ( $F_{1,1398} = 22.40$  and 17.07, respectively,  $P < 0.0001$  for both bands), the  $r^2$  values (the coefficient of determination for the regression) were too low ( $< 0.02$  in both cases) to conclude that variations in canopy height can be estimated from variations in the reflectance value in these bands. Furthermore, neither the reflectance values nor the values of the normalized difference vegetation index (NDVI) were significantly correlated with TAGB for either forest ( $r^2 < 0.05$ ,  $P > 0.05$  for all cases). The low  $r^2$  was attributed to the inability of data with medium spatial resolution (such as Landsat TM data) to account for the spatial variability of forest biophysical features that relate to TAGB. Therefore, using multispectral satellite images acquired only within visible, near-infrared, and shortwave infrared wavelengths (0.4–2.5  $\mu\text{m}$ ) is probably insufficient to detect local changes in TAGB. The wavelength range from 0.4 to 2.5  $\mu\text{m}$  is usually used by passive remote-

sensing satellites that record reflected incident rays after their interaction with the Earth's surface. Landsat TM is a typical example of this satellite system, and can thus be referred to as a passive optical-sensing system (Kramer, 2002).

Sader et al. (1989) reported that the NDVI values derived from Landsat TM images were poorly correlated with stand structure variables and TAGB in Puerto Rican and Costa Rican forests. Our results and those of the latter study suggest that the TAGB–reflectance curve obtained from these highly dense tropical rainforests were saturated, which means that regression slope approaches a plateau as the TAGB increases. The non-significant correlation between NDVI and TAGB strongly supports this view; that is, NDVI is saturated at  $LAI > 3 \text{ m}^2 \text{ m}^{-2}$  (Myneni and Williams, 1994; Moreau and Li, 1996; Carlson and Ripley, 1997; Gemmell and McDonald, 2000; Foody and Boyd, 2002). However, NDVI is widely used in analyzing the variations within vegetated areas with much lower density, which are mostly non-tropical forests. In these forests, NDVI shows strong functional relationships with leaf area index (LAI), woody stem biomass, and NPP (Gholz, 1982; Waring, 1983; Spanner et al., 1984; Running et al., 1986). Nevertheless, Landsat TM data can be used for qualitative evaluation and monitoring of forest regeneration, as has been recommended by the International Tropical Timber Organization (ITTO), using the forest canopy density technique (JOFCA, 1997). As an alternative tool, the use of active remote-sensing data, such as images collected using synthetic aperture radar (SAR), has been suggested for the evaluation of TAGB in forests, since variations in SAR measurements are related strongly to foliage and branch density, trunk biomass, and various structural aspects of forests (Le Toan et al., 1992; Foody et al., 1997; Luckman et al., 1998; Saatchi et al., 2000).

Alternatively, using high-resolution optical satellite images could permit analyses of the variation in canopy structure. However, calculating canopy heights or tree heights from passive optical sensor images is complicated by the need to measure the ground elevation if the bases of the tree trunks are not clearly visible throughout the target area (e.g., when the bases are obscured by snow in temperate-zone deciduous forests during the winter; Nakashizuka et al., 1995). In evergreen tropical forests, the markers

used for ground control points must be placed at the canopy surface so they are visible from the sky, as we did with the  $1 \text{ m} \times 1 \text{ m}$  markers, unless there are clearly visible landmarks within the image. Markers should be rigid and as small as possible to minimize damage from strong winds or other disturbances, and to maximize their longevity. Our markers remained in place for the duration of the study.

A high-resolution satellite such as IKONOS (Space Imaging Inc., Thornton, USA) or Quickbird (Digital Globe Inc., Longmont, USA) is theoretically able to establish the  $x$ – $y$  coordinates of the target area without such markers, although higher horizontal accuracies can still be obtained if ground control points are used. Horizontal accuracy is very important, particularly for monitoring chronological changes in canopy height and structure and in tree biomass on a local scale. In any case, regardless of the type of platform (satellite or aircraft), ground surveys remain necessary in order to measure the canopy height. This problem can be solved by using lidar (e.g., Airborne Laser Mapping System), which can simultaneously measure the canopy surface height and ground elevation by using wavelengths that reflect off the canopy surface and that pass through trees to reflect off the ground. However, because of the narrow spread of the laser beams, mapping large areas requires extensive flying missions (Dubayah and Drake, 2000) that cost a lot and that tax the endurance of small aircraft with short flying ranges. Use of the Laser Vegetation Imaging Sensor on airborne or satellite-borne instruments such as the Vegetation Canopy Lidar with a large footprint (area of coverage) might solve such problems (Blair et al., 1999; Means et al., 1999; Dubayah and Drake, 2000).

#### 4. Concluding remarks and suggestions for further study

We were able to establish an allometric relationship between tree height and DBH by combining aerial photographs with tree census data, including the DBH of individual trees. TAGB could be estimated by extrapolating this  $H$ – $D$  relationship to a given area for which the DBH values of all target trees were known. Using this method, we found that TAGB in the logged forest was significantly lower than that in the primary forest. It is notable that TAGB in the logged forest had

not fully recovered to the value in the primary forest even after 40 years. We also found that MCH and TAGB for a given area (a subplot) were significantly correlated. TAGB estimated using our canopy height model did not differ significantly from TAGB calculated from tree DBH data at randomly sampled points within the study plot. This suggests that developing a 3-D canopy height model for a target area permits the estimation of TAGB without requiring DBH measurements of individual trees or counts of tree densities. However, surveys of ground elevation are a prerequisite for the calculation of both canopy height and individual tree heights, because the latter measurements are based on aerial triangulation. Medium-resolution optical satellite images (such as Landsat TM) are inadequate for detecting local changes in TAGB in dense tropical rainforests. Thus, to estimate TAGB over a broad area, it would be necessary to use data from new-generation satellites with higher resolution or active remote-sensing data that reflect the spatial characteristics (e.g., volume) of forests. Nevertheless, it will also be necessary to use airborne remote-sensing systems such as lidar (laser profiling) to directly measure vegetation heights and to establish 3-D models of structurally complex tropical forests from the profile data.

Consequently, monitoring the structure and biomass of large areas could be improved by using laser profiling. However, laser profiling is expensive and may not always be available at all scales, in all regions, or under all weather conditions, and may be inappropriate for mapping large areas (Dubayah and Drake, 2000). In these cases, conventional stereoscopic analysis of aerial photographs permits 3-D structural analysis, and can be scaled up from small to large areas. Long-term chronological analysis of biomass changes or other aspects of the vegetation require the use of old data sets obtained before more modern technology was available; for example, stereoscopic sets of aerial photographs might be available for a target area. In such cases, canopy height analysis by means of aerial triangulation offers a good tool for establishing archival data and will provide information comparable to that in the most recent data sets. A combination of approaches and an examination of the consistency between conventional and new technologies will let investigators analyze chronological variations and scale up their methodology from

highly accurate monitoring of small areas to the monitoring of larger areas.

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