JARQ 44 (4), 435 – 446 (2010) http://www.jircas.affrc.go.jp

Estimating Diameter at Breast Height from Measurements of Illegally Logged Stumps in Cambodian Lowland Dry Evergreen Forest

Eriko ITO[1]*, Naoyuki FURUYA[2], Bora TITH[3], Samkol KETH[3], Ly CHANDARARITY[3], Sophal CHANN[3], Mamoru KANZAKI[4], Yoshio AWAYA[5], Kaoru NIIYAMA[6], Yasuhiro OHNUKI[7], Makoto ARAKI[7], Tamotsu SATO[7], Mitsuo MATSUMOTO[7] and Yoshiyuki KIYONO[7]

[1] Soil-Plant Ecosystem Group, Hokkaido Research Center, Forestry and Forest Products Research Institute (FFPRI) (Sapporo, Hokkaido 062–8516, Japan)
[2] Japan International Research Center for Agricultural Sciences (Tsukuba, Ibaraki 305–8686, Japan)
[3] Forest-Wildlife Research and Development Institute (Phnom Penh, Cambodia)
[4] Graduate School of Agriculture, Kyoto University (Kyoto City, Kyoto, Japan)
[5] River Basin Research Center, Gifu University (Gifu City, Gifu, Japan)
[6] Tohoku Research Center, FFPRI (Takizawa Town, Iwate, Japan)
[7] FFPRI (Tsukuba, Ibaraki, Japan)

Abstract
The Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) initiative requires accurate estimates of carbon stock changes in forested areas. However, estimating carbon emissions from stumps of various heights left by illegal loggers is difficult. To remedy this problem, we examined two methods of estimating diameter at breast height (DBH) from a reference diameter observation measured at any stump height. The one-reference diameter (OD) observation model estimates DBH from a single diameter observation using empirical coefficients derived mainly from emergent dipterocarp trees. The two-reference diameter (TD) observation model estimates DBH from two diameter observations and assumes a logarithmic relationship between diameter and height. Prediction data to establish the models were collected in Cambodian lowland evergreen forests that are undergoing intensive illegal logging of emergent dipterocarp trees for timber. The OD model performed better than the TD model in predicting DBH and is extremely practical, as it requires only a single diameter observation. Validation data previously collected in the Southeast Asian tropical forests established the general validity of the OD model. This study may improve the reliability of the REDD scheme by providing a reliable method to assess carbon emissions from Southeast Asian tropical forests.

Discipline: Forestry and forest products
Additional key words: biomass estimation, carbon stock change, dipterocarp, forest mensuration, REDD

This paper reports the results obtained in: (1) the Global Environment Research Funds "(B-082) Development of the forest degradation index and the carbon emission estimation method using PALSAR data (Ministry of the Environment, Japan), Ministry of Environment and Forest Administration, Cambodia, 2008-2010" and "(B-072) Research on the feasibility to estimate the GHG emissions reduction through avoiding deforestation (Ministry of the Environment, Japan); Ministry of Environment and Forest Administration, Cambodia; Department of Forestry, Lao PDR; 2007-2009"; (2) the Global Environment Research Coordination System (Ministry of the Environment, Japan); Forest Administration, Cambodia, 2008-2011; and (3) the KAKENHI 20770021 (Ministry of the Education, culture, sports, science & technology, Japan); Forest Administration, Cambodia, 2008-2010.
*Corresponding author: e-mail iter@affrc.go.jp
Received 10 December 2009; accepted 26 February 2010.

Introduction

The Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) initiative requires accurate estimates of carbon stock changes in forested areas[23]. Thus, carbon stock decreases due to logging must be estimated reliably. Cambodian seasonal tropical lowland forests with emergent dipterocarp trees are undergoing rapid degradation owing to intensive illegal logging (5.4 trees ha^{-1} $year^{-1}$ from Nov. 2006 to Mar. 2008; Furuya et al. unpublished). Dipterocarp trees constitute the greater part of the forest tree biomass in Cambodia and comprise 50% of total basal area (DBH > 10 cm)[12,13], which is similar to the basal area percentage of Kalimantan mixed dipterocarp forests[19]. The illegal logging of trees > 100 cm DBH and accompanying high damage to remaining trees seriously impact the natural forest ecosystem[20,21]. As illegal logging is unrecorded, we have to establish procedures to estimate the resulting decreases in carbon stocks.

A basic method of estimating tree biomass is via an allometric relationship between a tree reference diameter and tree biomass[11]. Diameter at breast height (DBH), which is measured at 1.30 m, is the most commonly used reference diameter[5]. Utilizing the remaining stumps of illegally logged trees is the most practical way to estimate tree biomass in the present situation. Very practical allometric relationships that use only DBH input and are applicable to Cambodian forests have been established to estimate above-ground biomass[3,8] and timber volume[6]. Using satellite imagery may be an alternative method for estimating the biomass of illegally logged trees; however, in practice, it is difficult to apply, given the costs of imagery, the availability of initial and final imagery, and the accuracy and precision of the resulting biomass estimates.

However, using the DBH of illegally logged stumps is often impossible because trees are cut at varying heights. A preliminary survey within the same area of this study (ca. 3 × 4 km^2) found that some illegally logged stumps of evergreen dipterocarps were more than 1.3 m tall (n = 189), whereas others averaged 0.76 m and ranged from 0.30 to 1.20 m in height (n = 118; Furuya et al. unpublished). This variation in stump height depends on the practices of individual logging groups (locals, personal communication). Deep burn scars from resin collection possibly result in logging at higher positions. When illegal logging expands into untapped areas, heights of logged stumps may lower.

DBH is often estimated using stump diameter without considering stump height[2], or stump diameter measured at a fixed height, such as 1.11 m, which was the mean stump height of an area studied in East Kalimantan[10]. This previous study is inapplicable to Cambodian illegal logging. Thus, developing a procedure to estimate DBH from a reference diameter observation of any height is important.

Numerous allometric DBH estimation models use diameter measurements at any height, but few of these models are applicable to Cambodian lowland evergreen forests. For example, allometric equations typically measure DBH at 4.5 feet[14,17]. The linear relationship between the diameter and height of a tree trunk does not fit to the swollen trunks of tropical trees with buttress roots[18], and tree size ranges do not correspond to those of Cambodian emergent trees[4].

The objective of this study was to establish a simple and robust allometric procedure for estimating DBH from a reference diameter observation at any height that is applicable to Cambodian lowland dry evergreen forests. We developed two different procedures: (1) a simple DBH estimation model using a single diameter and the height at which the diameter was measured; and (2) a more robust DBH estimation model using two diameter and height observations.

Methods

1. Study area

The study was conducted in Kampong Thom Province in central Cambodia (12.8°N, 105.5°E, ca. 50 km^2, Fig. 1). The altitude of our study area ranged from 80 to 100 m. The lowland dry evergreen forest type[22] of this area has largely disappeared in other Indochina Peninsula countries, with an area of 32,000 km^2 remaining in Cambodia (Fig. 1).

The diameters of 75 trees (60 living, 12 logged, and 3 naturally dead) were measured in Mar. 2009 (Table 1). Most of the sample trees were one of two emergent dipterocarps, *Dipterocarpus costatus* (n = 37) or *Anisoptera costata* (n = 28), both of which are major timber species often illegally logged. Additionally, we sampled the following frequent overstory species: *Sindora siamensis* (Leguminosae), which is mainly logged by concessionary forest managers, and the non-timber species *Irvingia malayana* (Irvingiaceae), *Fagraea fragrans* (Loganiaceae) and *Parinari annamensis* (Rosaceae). Our preliminary survey found that the mean (±SD) DBH of illegally logged timber trees was 87.6 ± 21.2 cm (n = 48). We measured at least three *D. costatus* or *A. costata* trees that fell within each 10-cm DBH gradation established between 30 cm and 140 cm DBH (except a ≤ 130-cm-size class, which had two samples).

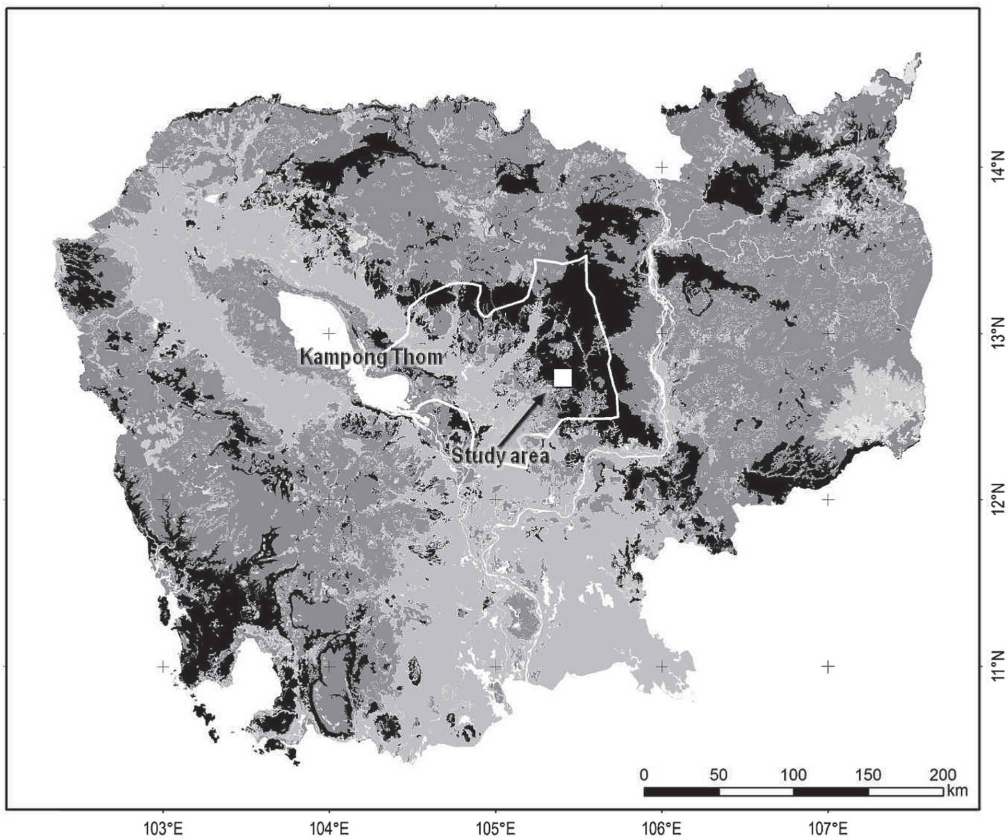

Fig. 1. Study area and vegetation map of Cambodia
■ : Lowland dry evergreen forest, ■ : Other forest, ■ : Non-forest, □ : Lakes and rivers.

Table 1. Species composition and diameter at breast height (DBH) of sampled trees in a Cambodian lowland dry evergreen forest

Family	Tree species	n	Mean ± SD [cm]	Range [cm]	Use
Dipterocarpaceae	*Dipterocarpus costatus*	37	85.6 ± 28.1	34.4–138.3	timber
Dipterocarpaceae	*Anisoptera costata*	28	86.1 ± 28.4	36.9–147.9	timber
Leguminosae	*Sindora siamensis*	5	58.2 ± 9.7	47.3–70.5	timber (previously)
Irvingiaceae	*Irvinsia malayana*	3	103.5 ± 23.5	82.9–129.1	non-timber
Loganiaceae	*Fagraea fragrans*	1	128.3	128.3	non-timber (coffin)
Rosaceae	*Parinari annamensis*	1	77	77	non-timber
	Total	76	84.7 ± 28.2	34.4–147.9	

To incorporate a wide range of stump heights, we established the following above-ground-level stem heights for diameter measurements of each tree: 30, 60, 90, 120, 130 (DBH), and 150 cm (Fig. 2a). Tree stem circumferences were measured using a girth tape, recorded to the nearest 0.10 cm, and converted to diameters. We did not measure a diameter if an obstacle was present (e.g., ant-hill) at the height class. We recorded remarks for each diameter measurement (e.g., buttress roots of all species and deep burn scars on *D. costatus* from resin collection). In all, we measured 427 diameters over bark to establish the allometric relationship.

2. Allometric Model Development

(1) One-reference diameter (OD) observation model

The one-reference diameter (OD) observation model involves an allometric equation that estimates DBH from a stump diameter (D), measured at any height, and the height at which the diameter is measured (H). Figure 2c presents the OD model procedure.

After examining several equations, we assumed a relationship between D (cm) and the natural logarithm of H (m; Fig. 2b) based on the tapering equation of Höjer[7]:

$$D = c_0 + c_1 \ln (H + 1.0). \quad [1]$$

The 1.0 m constant was added to H to eliminate the necessity of attempting to take the logarithm of a stump height at ground level (H = 0.0). The coefficients c_0 and c_1 are parameters indicating diameter at ground level and the sharpness of the curve fit of each tree trunk (i.e., curvature), respectively. Lower values of c_1 (hereafter, curve parameter c_1) which may be negative, indicate more sharply curved tree trunks.

To predict the curve parameter c_1 from a single diameter observation (i.e., a pair of D and H data), we used the following equation [2]:

$$c_1 = f(D, H). \quad [2]$$

After obtaining c_1 for an individual tree, c_0 is computed by substituting D and H into equation [1]. The

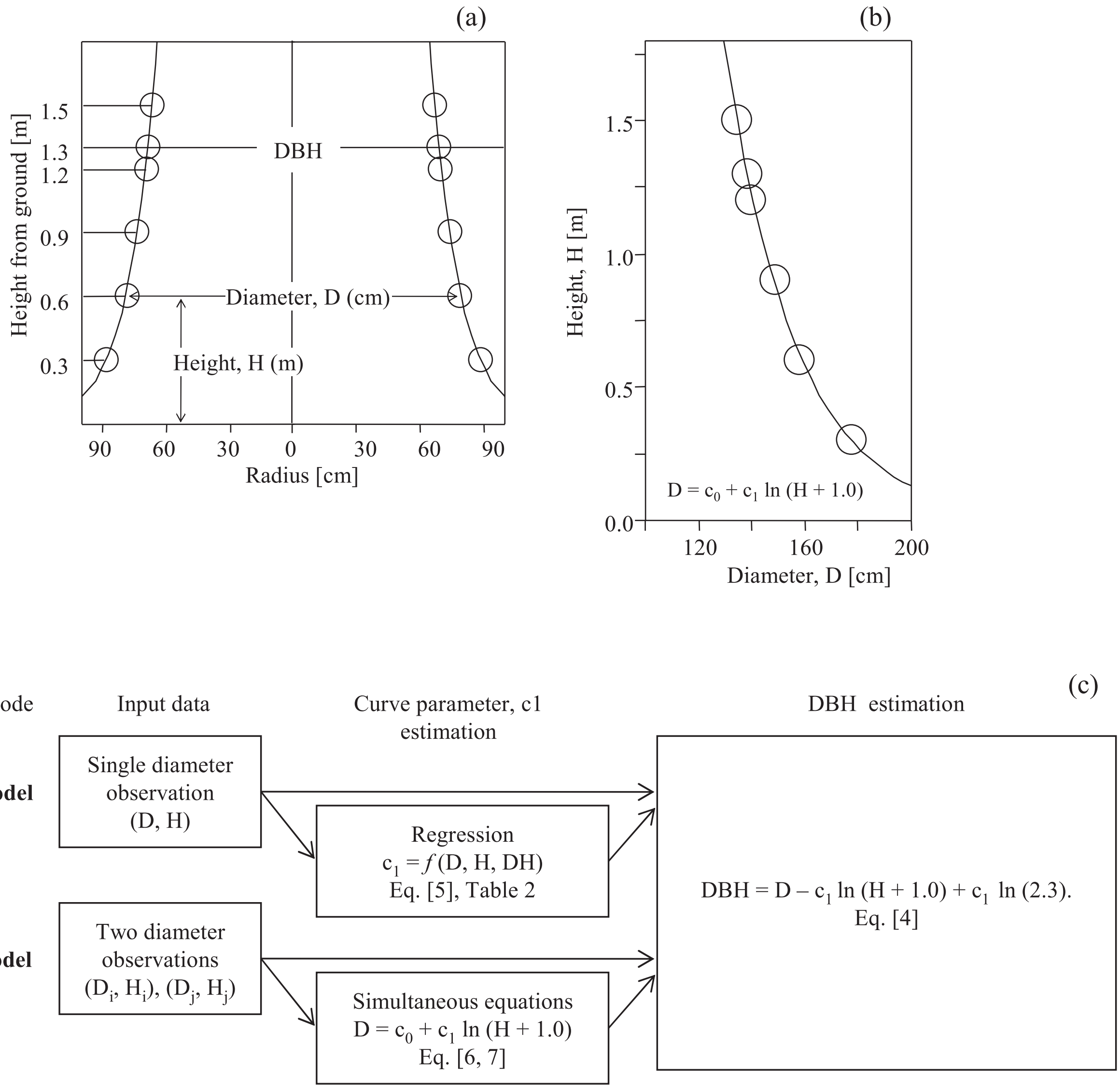

Fig. 2. Schematic representations of the one-reference diameter observation model (OD model) and two-reference diameter observation model (TD model)

(a): Schematic figure of tree trunk with diameter observations.

(b): Relationship between diameter (D; cm) and natural logarithm of height (H; m) at various diameter measurements of a sample tree (*Dipterocarpus costatus*, DBH = 138.3 cm).

(c): Model procedures, showing the computation of coefficient c_1 for a diameter observation.

DBH of the individual tree can then be easily computed by substituting H = 1.3 m. That is,

$$c_0 = D - f(D, H) \ln (H + 1.0) \quad [3]$$

$$DBH = D - f(D, H) \ln (H + 1.0) + f(D, H) \ln (1.3 + 1.0). \quad [4]$$

We developed multiple linear regression models to predict c_1 using D, H, and the interaction between D and H as independent variables and incorporating between-tree variability as a random effect. Dependent variable c_1 was absolute-log-transformed prior to analysis for normality. The final model is described as

$$\ln [|c_1|] = d_0 + d_1 D + d_2 H + d_3 DH \quad [5]$$

To compute c_1 as a dependent variable in the multiple linear regression model (Eq. [5]), we fitted a natural logarithmic curve (Eq. [1]) using a series of diameter observations for each sample tree and the least squares method (Fig. 2b). Because diameter measurements at the lower part of a trunk (e.g., 0.3 m and 0.6 m) occasionally worsened the curve fit, we eliminated diameter data that were measured at a position on the tree lower than the height at which the diameter was examined. For example, if c_1 was computed for a diameter measurement at 1.2-m height, a curve was derived from diameter measurements at heights of 1.2 m or more (i.e., 1.2, 1.3 and 1.5 m). A total of 277 diameter observations measured at less than 1.3 m were used to develop the multiple linear regression model described below. We estimated coefficients d_0, d_1, d_2, and d_3 from all of the pooled data.

(2) Two-reference diameter (TD) observation model

We established a two-reference diameter (TD) observation model to estimate DBH from stump diameters and heights measured at any two available heights (Fig. 2c). The model substitutes the two diameter observations into Eq. [1] to obtain a unique c_1 by solving the following simultaneous equations for the two diameter observations:

$$D_i = c_0 + c_1 \ln (H_i + 1.0) \quad [6]$$

$$D_j = c_0 + c_1 \ln (H_j + 1.0). \quad [7]$$

Note that no coefficient need be obtained in this method. Since we multichoose two observations from four measurements at different heights for each tree (i.e., 0.3, 0.6, 0.9, and 1.2 m), a total of six different TD models can be derived from one tree. Hence, our naming convention employs the two diameter observations used; thus, TD0912 indicates a model using measurements at 0.9- and 1.2-m heights. Using this procedure, we estimated the DBH of a total of 385 paired diameter observations.

3. Model Evaluation and Validation

We compared the predictive ability of the absolute values of residual error (cm) between the models. Residual errors were calculated as actual DBH minus estimated DBH. Positive and negative residual values indicated underestimation and overestimation of DBH, respectively. Pair-wise tests were conducted using paired *t*-tests. Test multiplicity was adjusted using the Bonferroni method. Contingency analysis using Fisher's exact test was conducted to examine the distribution of a categorical response variable that assessed the better of the two models, as conditioned by categorical factor values (i.e., the magnitude of the relationship between DBHs, as estimated by the OD and TD models).

Estimate errors in tree biomass caused by residual errors in DBH estimates were evaluated for dipterocarps from the data used to develop the model. Total (aboveground + belowground) tree biomass (B) could be estimated as follows:

$$B\,[Mg] = V\,[m^3] \times \rho\,[Mg\,m^{-3}] \times BEF\,[dimensionless] \times (R/S\ ratio + 1)\,[dimensionless],$$

where stem volume (V) was estimated from DBH [m] using the following equation for Cambodian evergreen dipterocarps with 15 cm ≤ DBH[6] : $V = -0.0971 + 9.503\,DBH^2$. Wood density (ρ), a biomass expansion factor (BEF) converting stem biomass to above-ground biomass, and the root to shoot (R/S) ratio that relates aboveground biomass to belowground biomass could be given as fixed values at the stand level[1]. The BEF can be applied at a single tree level although it is basically applied at stand level[9]. We calculated the ratio of tree biomass estimated from OD- or TD-modeled DBH to tree biomass estimated from measured DBH as an index of estimate errors. Note that the last three terms in the biomass equation, ρ, BEF, and R/S ratio, are reducible when calculating this ratio; however, each parameter can be obtained anywhere[1].

We validated the applicability of models established in other Southeast Asian forests using datasets that included DBH and at least one pair of D and H data that had been collected in Koh Kong Province, southwest Cambodia[8], Sebulu, East Kalimantan, Indonesia[24], and Pasoh, Malaysia[15]. Only trees greater than 20 cm DBH were used in the validation. The total numbers of trees from these studies used to validate the OD model were 8, 19 and 7, respectively, including nine dipterocarps (*Hopea* sp, *Shorea* sp, *Dipterocarpus* sp, and *Anisoptera* sp). The average DBH of the validation data was 39.1 ± 26.7 cm, with a range of 20.2 cm to 133.2 cm (n = 34). In all, 13 datasets were used to validate the TD model using diameter measurement heights of 0.0 m and 0.3 m. The DBH of the validation data averaged 35.1 ± 30.0 cm and ranged from 20.8 cm to 133.2 cm. We compared the model performances of the original and validation datasets after standardization by the height of diameter observations within the general linear model framework.

Statistical analyses were carried out using JMP6.0.

Results

1. One-reference diameter observation model (OD model)

A logarithmic regression curve (Eq. [1]) was fitted to the relationship between diameter and height at the measured diameter using all of the diameter observations for each sample tree ($0.87 < R^2 < 1.00$). The logarithmic regression fit better than did either a simple linear or an exponential regression (data not shown).

The curve parameter c_1 in Eq. [1] was well predicted by the multiple regression model using the independent variables D and H and the interaction between D and H ($p < 0.0001$, $R^2 = 0.93$). Coefficients of regression in the curve fit described larger trees having greater curvature, i.e., a smaller c_1 (Table 2, Fig. 3). The regression model derived from pooled data overestimated c_1 for non-timber trees (*F. fragrans*, *I. malayana* and *P. annamensis*).

In the OD model, diameter observations at lower heights resulted in larger absolute residual values (Table 3, Fig. 4). Large negative residual errors were often found in non-timber trees, corresponding to c_1 overestimations (Fig. 4).

2. Two-reference diameter observation model (TD model)

Absolute residual values were smallest in TD0912 and TD0612 models and largest in the TD0306 model (Table 4). The TD model often underestimated DBH, especially when diameters were observed at lower heights (Fig. 5). We found no consistent difference in residual errors among tree species and no relationship between residual error and tree size (Fig. 5).

3. Comparison of OD and TD models

We compared the predictive ability of the OD and TD models using diameter observation data derived from

Table 2. Coefficients for estimating curve parameter c_1 from diameter (D) and height (H) at which diameter is measured: ($\ln[|c_1|] = d_0 + d_1D + d_2H + d_3DH$; see also Eq. [5] in the main text)

n (tree)	n (observations)	d_0	d_1	d_2	d_3	R^2
76	275	1.68****	0.0146****	–0.82***	0.0068****	0.93

****: Regression coefficient significance level, $p < 0.0001$.
***: Regression coefficient significance level, $p < 0.001$.

Table 3. Absolute values of residual error in predicting DBH using the one-reference diameter observation model (OD model), with diameter observations measured at four different heights

Model code	Height of observation [m]	Data for paired comparison			Total examination		
		mean	SD	n	mean	SD	n
OD03	0.3	5.45[a]	5.85	56	5.45	5.85	56
OD06	0.6	2.77[b]	3.47	56	2.75	3.36	71
OD09	0.9	1.62[c]	2.08	56	1.69	2.09	75
OD12	1.2	0.41[d]	0.48	56	0.41	0.45	75

Means of paired comparison column data with different superscripts are statistically different at $p = 0.05$, based on paired t-tests adjusted using the Bonferroni method.

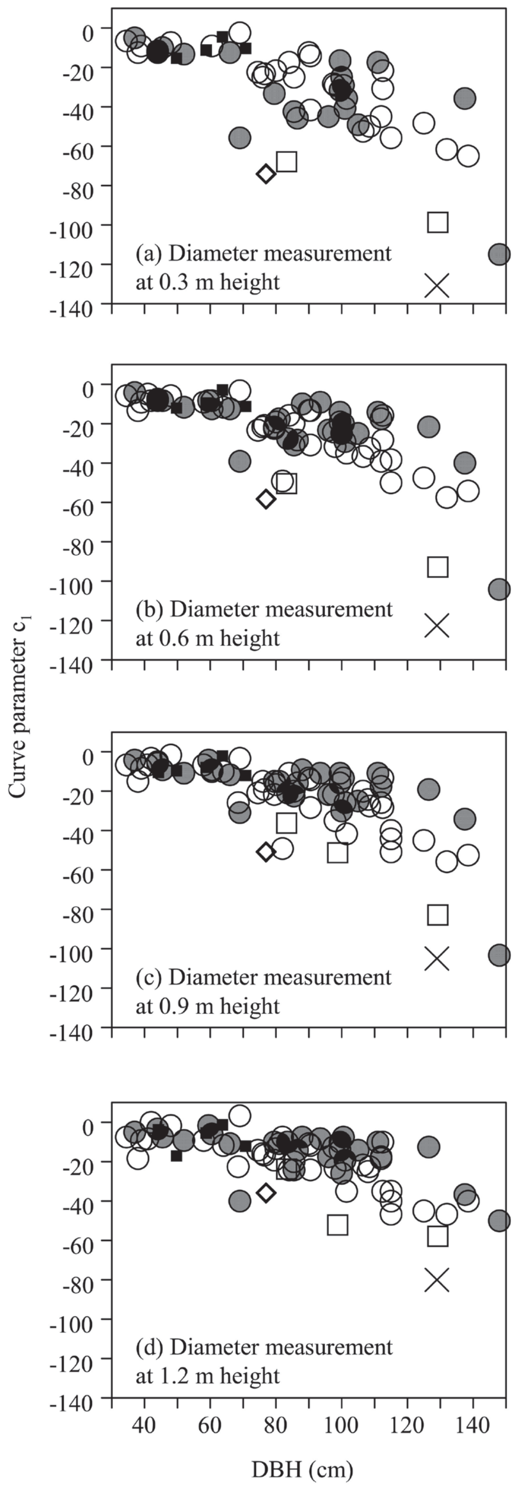

Fig. 3. Relationship between tree size (diameter at breast height, DBH) and curve parameter c_1 computed for diameter measurements at (a) 0.3 m, (b) 0.6 m, (c) 0.9 m, and (d) 1.2 m height

Timber tree species

● : *Anisoptera costata,* ○ : *Dipterocarpus costatus,*

■ : *Sindora siamensis.*

Non-timber tree species

× : *Fagraea fragrans,* □ : *Irvinsia malayana*,

◇ : *Parinari annamensis.*

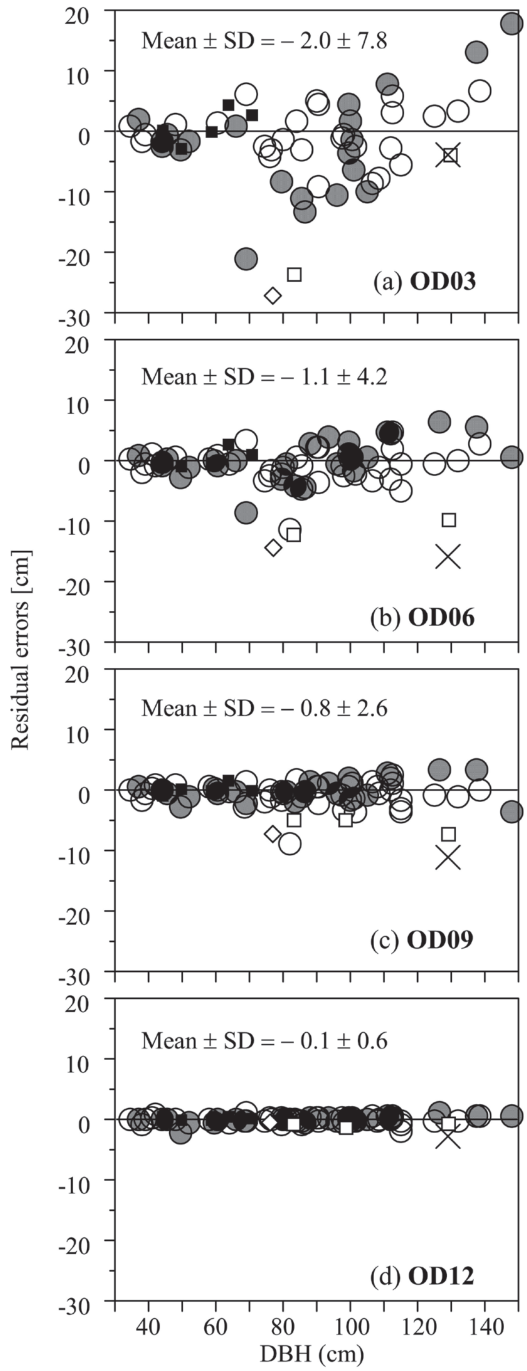

Fig. 4. Residual errors of one-reference diameter observation model (OD model) in estimating diameter at breast height (DBH)

Residual errors were derived from actual DBH minus estimated DBH values. DBH estimated using observations measured at (a): 0.3 m height (OD03), (b): 0.6 m (OD06), (c): 0.9 m (OD09), and (d): 1.2 m (OD12).

Timber tree species

● : *Anisoptera costata,* ○ : *Dipterocarpus costatus,*

■ : *Sindora siamensis.*

Non-timber tree species

× : *Fagraea fragrans,* □ : *Irvinsia malayana,*

◇ : *Parinari annamensis.*

57 trees measured at all four heights. The OD model that used diameter observations measured at the highest position performed best among the models for each height (Table 5). Some TD models (TD0609, TD0612 and TD0912) performed similarly to the best OD model at 0.9- and 1.2-m observation heights (Table 5).

The OD and TD model results used to estimate tree biomass had a mean uncertainty of 0−13% (Table 6). The error ratio of TD models using diameter observations at higher points (TD0609, TD0912) was as small as that of OD models (OD09, OD12), whereas TD0306 displayed a relatively larger error ratio than those of the OD03 and OD06 models.

Of 76 total sample trees, 18 had buttress roots. Trees with tall buttress roots displayed larger residual errors in both models ($p < 0.05$). The mean absolute value of TD model residual error was significantly greater than that of the control OD model, whereas buttress root measurements showed no difference (Table 7).

4. Model validation

Validation data for both the OD and TD models performed similarly to those for the model development dataset (Table 8; see also Table 3). For the OD model, the mean absolute residual values of the validation dataset were significantly smaller than were those of the model development dataset ($p < 0.002$). However, TD model validation data underestimated DBH (Table 8). The mean absolute values of the residuals of OD03 model validation data measured at 0.0 m and 0.3 m heights did not differ significantly from those of the TD0003 model (Table 8).

The mean absolute values of OD model residuals did not differ significantly between dipterocarp trees (3.60 ± 4.60, n = 9) and non-dipterocarp trees (2.43 ± 3.98, n = 25). Validation data for the TD model did not show any improved predictive ability for non-dipterocarp trees (data not shown).

Discussion

1. Model approach

Empirical relationships have often been used to estimate DBH from a reference diameter and the height at which diameter was measured: for example, $DBH = D[b_0 + b_1\ln(H) + b_2(\ln(H))^2 + b_3(DH)]$ [14]; $DBH = D[b_0 + b_1\ln(H) + b_2(DH)]$ [17]; and $DBH = b_0[D^{b1}H^{b2}]$ [4]. In contrast, we adopted an allometric approach based on the logarithmic relationship between tree trunk diameter and height (Eq. [1], Fig. 2). Tree trunk shape has been expressed empirically as a simple linear relationship[18] or theoretically as an exponential relationship within the Shinozaki's pipe model theory[16]. However, possibly because these relationships were derived from measurements higher than DBH or buttress roots on the tree, we found a logarithmic relationship to be much better at representing the shape of a tree trunk around a stump.

Based on this assumption of a logarithmic relationship, we created the OD and TD models, which estimate DBH from reference diameters measured at any height. Our model approach enhances the applicability of DBH estimation in three ways.

First, we investigated the height at which the reference diameter is measured. We demonstrated that better DBH estimates are achieved when the reference diameter is measured at approximately 1.3 m (Tables 3 and 5), as did a previous study[17]. Moreover, in the TD model, TD0912 estimates were notably superior to those of TD0312. Unexpectedly, a wider range of data did not produce better regression analysis estimates, indicating that fixing the height of the reference diameter reduces

Table 4. Absolute values of residual error of the two-reference diameter observation model (TD model) in predicting DBH

Model code	Heights of observation [m]	Data for paired comparison			Total examination		
		mean	SD	n	mean	SD	n
TD0306	0.3, 0.6	7.00[a]	7.88	56	7.00	7.88	56
TD0309	0.3, 0.9	3.18[b]	3.07	56	3.18	3.07	56
TD0609	0.6, 0.9	1.98[c]	2.02	56	1.83	1.89	71
TD0312	0.3, 1.2	0.78[d]	0.75	56	0.78	0.75	56
TD0612	0.6, 1.2	0.52[e]	0.54	56	0.52	0.54	71
TD0912	0.9, 1.2	0.47[e]	0.52	56	0.48	0.56	75

Means of paired comparison column data that do not share a common superscript letter are statistically different at $p = 0.05$, based on paired t-tests adjusted using the Bonferroni method.

the probability of more accurate estimation. Thus, reference diameters should be measured as near 1.3 m as possible.

Second, the allometric model approach permitted both models to estimate diameter at any height (e.g., 1.2 m, previously used as DBH in Japan, or 4.5 feet used in the US) by substituting 1.3 m for any value in Eq. [4], although error may increase when estimating diameters far from 1.3 m. This DBH height overcomes difficulties of previous studies; McClure[14] (1968) employed allometric equations to estimate DBH measured at 4.5 feet using only an empirical nonlinear relationship that could not estimate DBH at 1.3 m.

Finally, our model approach in both the OD and TD models achieved considerable predictive utility over a wide range of tree sizes (30 < DBH < 150 cm; Figs. 4 and 5), a range as great as that achieved by a model using a reference diameter measured at a fixed height[10]. Our success was mainly due to the computation of a curve parameter, c_1 (Eq. [1]), that reflected tree size (Fig. 3).

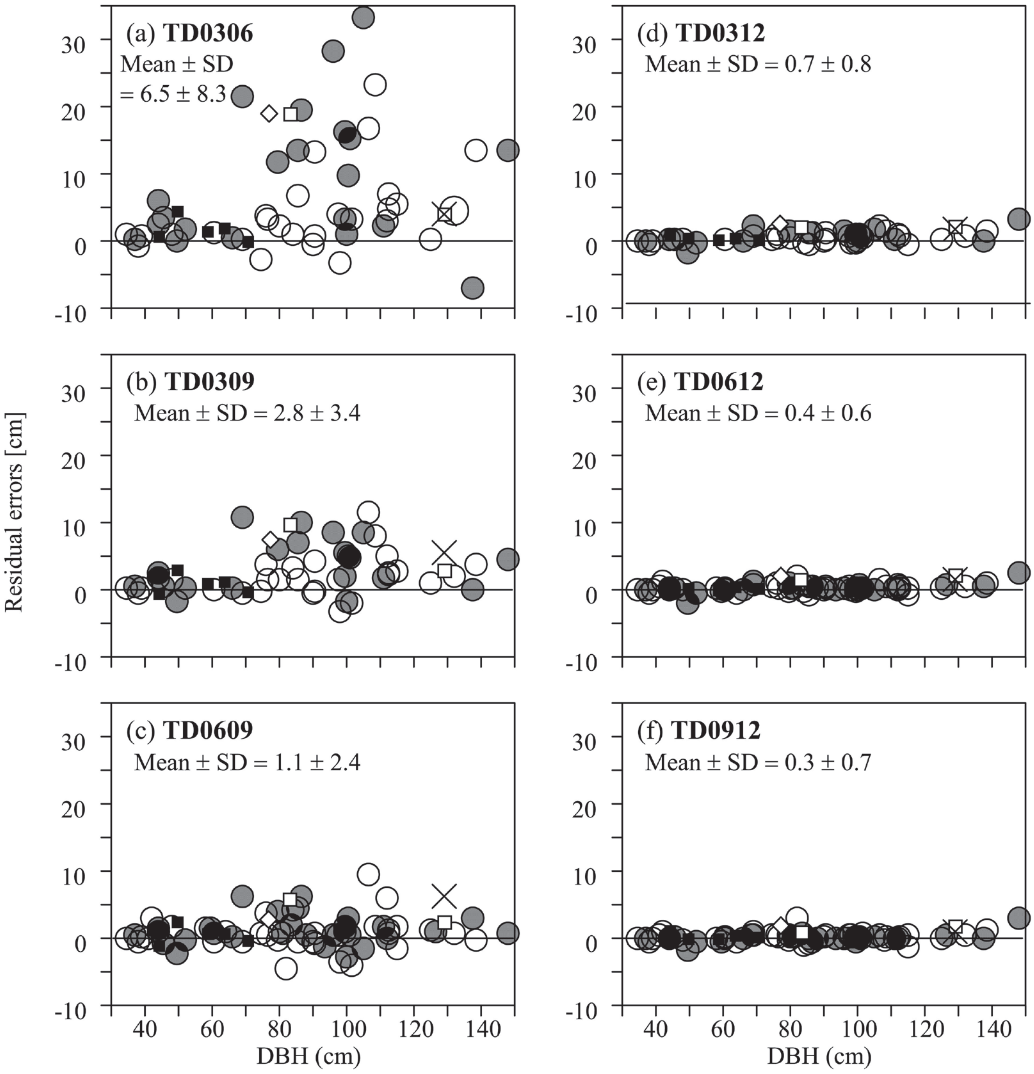

Fig. 5. Residual errors of two-reference diameter observation model (TD model) in estimating diameter at breast height (DBH)

Residual errors were derived from actual DBH minus estimated DBH values. DBH estimated using observations measured at (a): 0.3 and 0.6 m height (TD0306), (b): 0.3 and 0.9 m (TD0309), (c): 0.6 and 0.9 m (TD0609), (d): 0.3 and 1.2 m (TD0312), (e): 0.6 and 1.2 m (TD0612), and (f): 0.9 and 1.2 m (TD0912).

Timber tree species

● *: Anisoptera costata,* ○ *: Dipterocarpus costatus,* ■ *: Sindora siamensis.*

Non-timber tree species

× *: Fagraea fragrans,* □ *: Irvinsia malayana*, ◇ : *Parinari annamensis*.

2. Predictive performance of the OD and TD models

The OD model displayed considerable predictive ability based on the prediction data (Table 3), although it was less accurate for non-timber trees (Fig. 4). Even for validation data that included different tree species in the prediction data, the OD model surpassed the predictive ability of the prediction data (Table 8). We quantified the potential error in the tree biomass estimations of OD models, which could prove useful in carbon emission accounting (Table 6).

The TD model has less predictive ability than does the OD model (Table 5), particularly when diameter observations at lower heights are used. The underestimation of DBH (Fig. 5, Table 8) would result in underestimation of carbon emissions from deforested and degraded forest areas. However, the predictive ability of the TD model is relatively better than that of the OD model for non-timber trees (Figs. 4 and 5), trees with buttress roots (Table 7), and validation data (Table 8). This result met our expectation of robust TD model performance; however, the TD model was not significantly superior to the OD model.

The underperformance of the OD model with non-timber trees (Fig. 4) could result in DBH estimate errors and hence, in carbon emission errors. However, the residual errors resulted from the small curve parameter c_1, indicating a more sharply curved tree trunk. Most logged tree species have straight trunks for timber use. Thus, the OD model, which uses coefficients mainly derived from dipterocarp trees, could be generally applied to tree species logged for timber. In this context, the OD model would be useful in forests degraded by illegal logging.

The irregular trunk forms of many tropical forest trees, such as those caused by buttress roots[24], gnarls and deep burn scars from resin collection, could result in large DBH estimate residuals, as this study revealed (Table 7). Although the biomass of trees with buttress roots has been estimated[25], future studies need to quantify the

Table 5. Mean absolute values of residual error of OD and TD models for each observed height (m)

Model code	Available observation height [m]			
	0.3	0.6	0.9	1.2
OD Model				
OD03	5.45	5.45[a]	5.45[a]	5.45[a]
OD06	–	2.77[b]	2.77[bc]	2.77[bc]
OD09	–	–	1.62[d]	1.62[d]
OD12	–	–	–	0.41[f]
TD Model				
TD0306	–	7.00[e]	7.00[e]	7.00[e]
TD0309	–	–	3.18[b]	3.18[b]
TD0609	–	–	1.98[cd]	1.98[cd]
TD0312	–	–	–	0.78[g]
TD0612	–	–	–	0.52[f]
TD0912	–	–	–	0.47[f]

Hyphens (–) indicate a lack of measurements. Diameter observations of 56 trees measured at all four heights were compared. Height line data that do not share a common superscript letter are statistically different at p = 0.05, based on paired t-tests adjusted using the Bonferroni method.

Table 6. Estimated biomass error of dipterocarp sample trees

Model code	Error ratio of dipterocarp tree biomass estimation				Residual error (cm)	
	mean	SD	range	n	mean	SD
OD Model						
OD03	1.04	0.16	0.77–1.72	47	−1.22	6.76
OD06	1.02	0.07	0.90–1.30	62	−0.40	3.08
OD09	1.01	0.04	0.95–1.23	65	−0.42	1.90
OD12	1.00	0.01	0.96–1.04	65	−0.03	0.49
TD Model						
TD0306	0.87	0.16	0.46–1.10	47	6.60	8.52
TD0609	0.98	0.06	0.82–1.11	62	0.97	2.36
TD0912	1.00	0.02	0.93–1.02	65	0.23	0.67

The error ratio indicates the ratio of tree biomass calculated from estimated DBH to that of measured DBH (dimensionless). The mean residual error (cm) of each OD and TD model is also shown.

Table 7. Residual error of one- and two-reference diameter observation models (OD and TD models) that differ in presence of buttress roots

Model code	Control				Buttress root			
	mean	SD	n	*p*	mean	SD	n	*p*
OD	1.25	1.76	177	0.0003***	4.30	4.67	25	0.1
TD	2.12	4.07			7.39	8.21		

For the OD model, the best results at each available height are shown.

Table 8. Residual error of one- and two-reference diameter observation models (OD and TD models) of validation datasets

Model Code	Height of observations [m]		Absolute value of residual error		Residual error	
		n	mean	SD	mean	SD
OD00	0	13	4.51	5.94	1.82	7.33
OD03	0.3	19	2.34	3.30	1.06	3.93
OD_{other}	0.4–1.0	9	1.12	1.10	–0.56	1.49
TD0003	0.0, 0.3	13	5.24	5.01	4.98	5.29

accuracy and precision of biomass estimates of trees with irregularly shaped trunks.

Conclusions

This study established allometric procedures for estimating DBH from reference diameter observations at any height. We develop two procedures applicable to Cambodian lowland dry evergreen forests: (1) the OD model, which estimates DBH from a single diameter observation, employs empirical nonlinear regression to estimate the curve parameter c_1 using the variables D, H and DH; and (2) the TD model, which estimates DBH from two diameter observations and is based on the assumption of a logarithmic relationship between diameter and height, showed enhanced DBH estimations.

The OD model performed well in estimating DBH, and the accuracy of these estimates was quantified as an error range of tree biomass estimation. The TD model performed less well in DBH estimation, although the robustness of the TD model suggests that it may work well in non-dipterocarp forests. The OD model is a practical tool for estimating DBH, particularly of dipterocarps or other timber trees with straight trunks. Frameworks of the model could be applied to the other trees of Southeast Asian tropical forests. This study may improve the reliability of the REDD scheme by providing practical tools to estimate carbon emissions of Southeast Asian tropical forests.

Acknowledgments

We thank H.E. Sokhun Ty, Head of Cambodian Forest Administration, for his valuable cooperation on a wide range of issues. We are indebted to Prof. K. Kikuzawa for his comments. This work was supported in part by KAKENHI 20770021 and the Global Environment Research Fund (B-072, B-082), as well as Research by Global Environment Research Coordination System, funded by the Ministry of the Environment Japan.

References

1. Brown, S. (1997) Estimating biomass and biomass change of tropical forests: A primer (FAO forestry paper 134). Food and Agriculture Organization, Rome, Italy. http://www.fao.org/docrep/W4095E/W4095E00.htm.
2. Bylin, C. V. (1982) Estimating dbh from stump diameter for 15 southern species. U.S. Department of Agriculture (USDA), Forest Service, Southern Forest Experiment Station, Research Note SO-286.
3. Chave, J. et al. (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia,* **145**, 87–99.
4. Chhetri, D. B. K. & Fowler, G. W. (1996) Estimating diameter at breast height and basal diameter of trees from stump

measurements in Nepal's lower temperate broad-leaved forests. *For. Ecol. Manage.,* **81**, 75–84.
5. Chiba, Y. (1998) Architectural analysis of relationship between biomass and basal area based on pipe model theory. *Ecological Modelling,* **108**, 219–225.
6. Department of Forestry and Wildlife (DFW) et al. (2004) Forest systems research and modeling handbook. Forest concession management and control pilot project, The World Bank Project Credit No. 3365-KH, Forestry administration, Phnom Penh, Cambodia.
7. Höjer, A. (1903) Growth of Scots pine and Norway spruce. Stockholm, Bilaga till. Loven, F.A. om vara barrskorar.
8. Hozumi, K. et al. (1969) Production ecology of tropical rain forests in southwestern Cambodia. I. Plant biomass. *Nature and Life in South-east Asia,* **6**, 1–56.
9. IPCC (2003) IPCC, Good practice guidance for land use, land-use change and forestry. *IPCC National Greenhouse Gas Inventories Programme.* Hayama, Japan.
10. Iskandar, H., Hubble, D. L. & MacDicken, K. G. (2003) Estimating DBH of commercial trees from stump measurement in Malinau, East Kalimantan. *J. Trop. For. Sci.,* **15**, 502–504.
11. Iskandar, H. et al. (2006) A comparison of damage due to logging under different forms of resource access in East Kalimantan, Indonesia. *For. Ecol. Manage*., **237**, 83–93.
12. Kao, D. & Iida, S. (2006) Structural characteristics of logged evergreen forests in Preah Vihear, Cambodia, 3 years after logging. *For. Ecol. Manage*., **225**, 62–73.
13. KimPhat, N. et al. (2000) Stand dynamics of dipterocarp trees in Cambodia's evergreen forest and management implications−a case study in Sandan district, Kampong Thom. *J. Jpn. For. Plan.,* **6**, 13–23.
14. McClure, J. P. (1968) Predicting tree D. B. H. from stump measurements in the Southeast. http://www.srs.fs.usda.gov/pubs/rn/rn_se099.pdf.
15. Niiyama, K. et al. (2010) Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. *J. Trop. Ecol.,* **26**, 1–14.
16. Oohata, S. & Shinozaki, K. (1979) A statistical model of plant form-Further analysis of the pipe model theory. *Jpn. J. of Ecol.,* **29**, 323–335.
17. Raile, G. K. (1978) Estimating d.b.h from stump dimensions. *In* Proceedings, 1977 Midwest Forest Mensurationists Meeting, General Technical Report NC-46, U.S. Department of Agriculture (USDA), Forest Service, North Central Forest Experiment Station, 30–33.
18. Raile, G. K. (1982) Estimating stump volume. Research Paper NC-224, U.S. Department of Agriculture (USDA), Forest Service, North Central Forest Experiment Station, 1–4.
19. Sist, P. et al. (1998) Harvesting intensity versus sustainability in Indonesia. *For. Ecol. Manage*., **108**, 251–260.
20. Sist, P. & Nguyen-Th, N. (2002) Logging damage and the subsequent dynamics of a dipterocarp forest in East Kalimantan (1990−1996). *For. Ecol. Manage*., **165**, 85–103.
21. Sist, P. et al. (2003) Reduced-impact logging in Indonesian Borneo: some results confirming the need for new silvicultural prescriptions. *For. Ecol. Manage*., **179**, 415–427.
22. Tani, A. et al. (2007) Principal forest types of three regions of Cambodia: Kampong Thom, Kratie, and Mondolkiri. *In* Forest environments in the Mekong River Basin, eds. Sawada, H. et al., Springer, Tokyo, 195–207.
23. UN FCCC (2009) Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks. Framework convention on climate change, Technical paper, GE.09–70130.
24. Yamakura, T. et al. (1986) Tree size in a mature dipterocarp forest stand in Sebulu, East Kalimantan, Indonesia. *Southeast Asian Studies,* **23**, 452–478.
25. Yamakura, T. et al. (1987) Tree form in a mixed dipterocarp forest in Indonesian Borneo. *Ecol. Res.,* **2**, 215–227.