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PART B-6:
Tree allometric equations in Evergreen broadleaf, Deciduous, and Bamboo forests in the Central Highland region, Viet Nam

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Tree allometric equation development for estimation of forest above-ground biomass in Viet Nam -- Evergreen broadleaf, Deciduous, and Bamboo forests in the Central Highland region

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EXECUTIVE SUMMARY

The aim of this study is to develop allometric equations for biomass estimation for three forest types in the Central Highland region of Viet Nam, namely, evergreen broadleaf (EB) forests, deciduous forests and bamboo (*Bambusa procera) forests*.

Two sample plots with area of 1 ha (100 x 100 m) were set up for EB forests, one sample plot of the same size for deciduous forests and one sample plot of 0.5 ha (50 x 100 m) was established for bamboo forests. Sample plot measurements studied forest structure including tree species composition and tree density, as the base for selecting sample trees for biomass measurement. The selection of sample trees and bamboo follows dominant trees species and number of trees in each diameter at breast height (DBH) class.

Destructive measurement was applied to measure fresh above ground biomass (AGB). A total of 115 sample trees with DBH of 6.1-74 cm were selected from EB forests for fresh and dry biomass measurement and wood density (WD) analysis, in which 105 sample trees were used for equations development and ten trees were used to validate the developed equations. For deciduous forests, 68 sample trees with DBH of 7.2-52.2 cm, were studied, of which 60 trees for equations development and eight trees were used for model validation. A total of 138 sample bamboos were felled for equation analysis, of which, 20 were for equation validation. Statistical Package for Social Science (SPSS) was applied to analyze relationship between biomass and predictor variable. Variables used for regression analysis were DBH, tree height (H) and WD.

The results show that there is strong relationship between AGB and predictor variables of DBH, H and WD. The optimal equation for biomass estimation at tree level for EB forests is:

$AGB = 0.222*DBH^{2.387}$ ($R^2 = 0.96$) and

$AGB = 0.098*\exp(2.08*Ln(DBH) + 0.71*Ln(H) + 1.12*Ln(WD))$ ($R^2 = 0.98$)
with deviation of 14.1-17.6%.

Fordeciduous forests, the optimal model for biomass estimation is:

$AGB = 0.14*DBH^{2.31}$ ($R^2 = 0.93$)
with deviation of 26.9%.

For bamboo, the optimal equations suggested for biomass estimation is:

$AGB = 0.182*DBH^{2.16}$
with $R^2 = 0.86$ and deviation of 23.7%.

The results indicate that compared to the models for biomass estimation suggested by Brown (1997), Chave (2005) and Basuki *et al* (2009), the suggested models developed in this study can generate higher realibility in biomass estimation of these forest types in Central Highland of Vietnam.

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ABBREVIATIONS AND ACRONYMS

AE	Allometric equation
AGB	Above ground biomass, expressed in kg/tree or ton/ha
Bm	Measured biomass
Bp	Predicted biomass
DBH	Diameter at breast height at 1.3 m, expressed in cm
D/F	Ratio of dry biomass to fresh biomass
E	Error, expressed in %
EB	Evergreen Broadleaf
FAO	Food and Agriculture Organization
FIPI	Forest Inventory and Planning Institute
G	Basal area, expressed in m^2 per ha
H	Total tree height, expressed in meter
IV	Important value index, expressed in %
M	Standing wood volume, expressed in m^3/ha
Max	Maximum value
Mean	Average value
Min	Minimum value
MRV	Measuring, Reporting and Verification
N	Number of trees or bamboos, expressed in trees or bamboos/ha
N_O	Number of old bamboos, expressed in bamboo/ha
N_M	Number of mature bamboos, expressed in bamboo/ha
N_Y	Number of young bamboos, expressed in bamboo/ha
n	Number of sample observations
NA	Not Available
REDD	Reducing Emissions from Deforestation and forest Degradation
RCFEE	Research center for Forest Ecology and Environment
R^2	Coefficient of determination
SE	Standard Error
SPSS	Statistical Package for Social Science
STD	Standard Deviation
TNHH	Liability limited company
TNU	Tay Nguyen University
UN-REDD	United Nations program on REDD
VFU	Vietnam Forestry University
WD	Wood density, expressed in g/cm^3 or kg/m^3

1 INTRODUCTION

This study aims to: establish allometric equations for forest biomass estimation of individual tree for natural forests in the Central Highlands region of Vietnam, contributing to the implementation of REDD+ activities in Vietnam.

2 MATERIAL AND METHODS

2.1 Sampling strategy

2.1.1 Location and design of the plots

Description of the sample plots

The destructive measurements were implemented in Lam Dong Province of the Central Highlands region of Vietnam. The three forest types are: (i) EB forests; (ii) deciduous forests; and (iii) bamboo forests.

Sample plots for EB forests were set up in 390A compartment in Loc Bac Commune of Bao Lam District; the location of deciduous forests was in 330 compartment in Proh Commune of Don Duong District; and sample plots of bamboo forests were in 392A compartment in Loc Bao Commune of Bao Lam District. Location map of the study sites is shown in Figure 1.

The study sites are located at hilly and mountainous areas with strong dissection of valley and streams. The slope gradient fluctuates from 5^{o} to 25^{o}. In the sites, there are several high mountain ranges with elevation ranging between 250-1,100 m above sea level. Sample plots were established at the elevation of 558 m for bamboo forests and 677 m for the EB and deciduous forests.

The sites are within the tropical monsoon climate. The climate has two distinct seasons; rainy and dry. The rainy season starts in the middle of April and ends in November. Rainfall between July to the end of September accounts for approximately 70% of annual rainfall. The average rainfall is about 1,800-2,200 mm in Bao Lam District and 800-1,000 mm in Don Duong District. The average temperature is about 24^{0}C.

Soil under the EB and bamboo forests, which was formed from Basalt rock, is classified as Ferrasols and accounts for 66.6% of total provincial land area. Generally, the soil contains a thick layer of light to medium physical texture, with pH value of 4-5.5. Soils are generally suitable for forest development and agriculture. In the study site of deciduous forests, the soil found is mainly Acrisols developed on sandstone, with light to medium physical texture, soil layer thickness of 50-100 cm and pH ranging from 4-6.

The study sites for EB and bamboo forests is under management of Loc Bac One-Member Liability Limited Forestry Company. The Company manages a total forest area of 28,804 ha. The company's natural forests are mainly composed of medium, poor quality and regrowth forests[1]. Rich forests occupy 0.58% of the company's forest area. The main types of forests include natural EB forests, plantations, natural bamboo forests and mixed woody and bamboo forests. Forests under the company's management include approximately 85% of production forests, and 15% of protection forests. Survey plots under this study were located in production forests.

The destructive measurement sites for deciduous forests are under the management of Don Duong One Member Liability Limited Forestry Company. The forest area managed by the company is 19,252 ha. The main forest types are EB forests, covering approximately 40% of all forests of the company; deciduous forests account for 25%, and plantation forests covers approximately 11%. Forests under

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[1] General classifications of volume and status based forest classifications in the Vietnamese forest inventory system.

the company’s management include approximately 90% of production forests, and 10% of protection forests. Survey plots under this study were located in production forests.

Sample plot selection and establishment

Sample plots were selected and established in the three forest types. The area of sample plots is 1 ha (100 x 100 m) for EB and deciduous forests and 0.5 ha (50 x 100 m) for bamboo forests. Total sample plots established are four, of which two plots are for EB forests and one plot each for deciduous and bamboo forests.

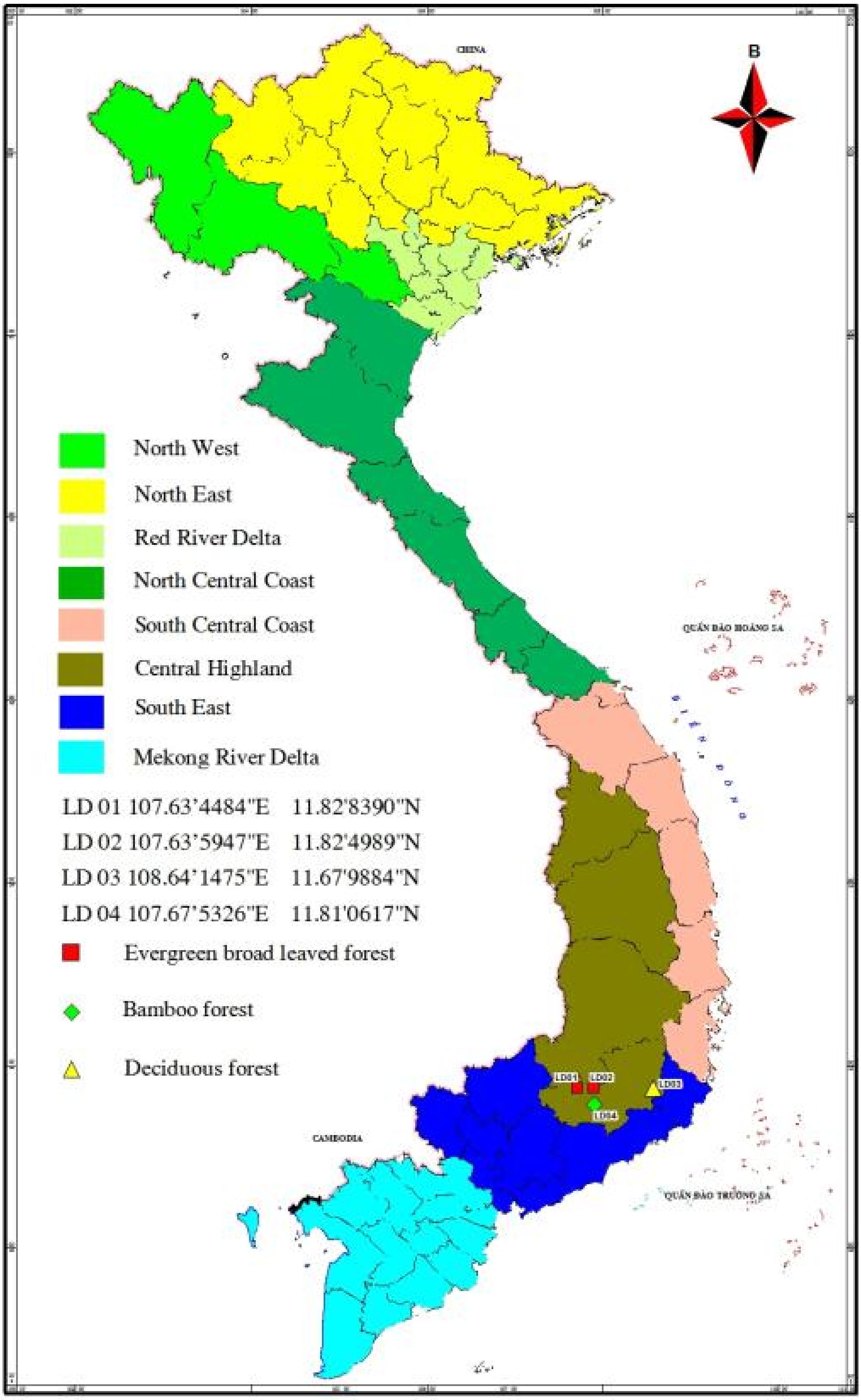


Figure 1 Map of destructive measurement plot sites

2.1.2 Selection of the sampling trees

Trees were classified by DBH class;

Diameter classes for EB forests are (in cm): 5-14.9; 15-24.9; 25-34.9; 35-44.9; 45-54.9; 55-64.9; 65-74.9 and > 75.

Diameter classes for deciduous forests are (in cm): 5-14.9; 15-24.9; 25-34.9; 35-44.9; 45-54.9 and > 55.

In addition to the DBH classes, trees for felling were determined to meet the following criteria: i) distribution of tree numbers by DBH class (N-DBH) and distribution of tree numbers by total basal area (N-G); ii) dominant species with importance value (IV) greater than 5%. The sample trees for felling were then selected randomly from the trees meeting the above criteria. In EB forests, the total basal area (G) of sample trees was 23% of G within the plot, and 27% for deciduous forests (**Error! Reference source not found.**).

Table 1 Rate of sampling for EB and deciduous forests

ID	Diameter class (cm)	EB forest				Deciduous forest			
		Total tree/ha	G (m^2/ha)	No. of felled trees	% of G of felled trees (%)	Total tree/ha	G (m^2/ha)	No. of felled trees	% of G of felled trees (%)
1	5-15	1269	8.03	23	2.3	463	4.13	17	4.3
2	15-25	244	7.02	21	9.4	205	5.89	17	9.3
3	25-35	107	7.59	22	21.7	50	3.34	19	40.8
4	35-45	62	7.94	22	36.0	10	1.21	9	87.3
5	45-55	45	8.74	11	23.8	6	1.17	6	98.3
6	55-65	24	6.91	9	37.3	0		0	0
7	65-75	9	3.53	7	77.7	0		0	0
8	> 75	6	4.92	0	0	0		0	0
Total		1766	54.68	115	23.3	734	15.74	68	27.3

For bamboo forests, all bamboos were classified into the following DBH classes (in cm): 2-3; 3-4; 4-5; 5-6; 6-7; 7-8; 8-9 and > 9; and classified into age classes s of “young”, “medium” and “old” (see section 2.4 on details of age classes). The number of sample bamboos for felling to measure above ground biomass (AGB) was 138 bamboos.

Table 2 Number of sample bamboos felled

ID	Diameter class (cm)	Total bamboo/ha	No. of felled bamboo	Felled bamboos by age class		
				Young	Medium	Old
1	2-3	52	15	2	1	12
2	3-4	378	24	3	8	13
3	4-5	582	18	4	7	7
4	5-6	724	23	3	7	13
5	6-7	870	18	9	3	6
6	7-8	420	23	6	7	10
7	8-9	46	15	5	3	7
8	> 9	4	2	0	0	2
Total		3076	138	32	36	70

2.2 Variables measurement and calculation for volume and biomass

2.2.1 Field measurements

Sample plot measurements

All activities for destructive measurement, and dry mass and WD analysis were implemented following the draft Guidelines on Destructive Measurement for Forest Biomass estimation prepared by UN-REDD Program (UN-REDD Vietnam 2012). The following summarizes the main steps for biomass measurement and allometric equation development

Information on coordinate at plot centre, slope, and soil type were collected for EB and deciduous forests.

All trees with diameter at breast height (DBH) over 5 cm were numbered and tree species defined.

For bamboo forests, after the establishment of sample plots, measurements were applied to bamboos with DBH over 2 cm. In addition, bamboos were categorized according to three age classes of “young”, “medium” and “old” (see section 2.4 for details on age classes).

Measurement of fresh biomass

In woody forests (EB and deciduous forests), chain saws were used to fell sample trees for measuring fresh biomass. The sample trees were felled following logging procedures and the cutting point was at ground level. After sample trees were felled, then diameter at stump, DBH and total tree height (H) were measured. The tree was then cut and separated then weighed by components of bole, branch and foliage. All data were recorded carefully in field notes.

For bamboo, knives were used to cut down the sample bamboo at ground level. DBH, H were measured and age class determined. The age of bamboo was determined based on the following requirements:

- "Young": bamboos aged 1-2 years with adequate development of branches and leaves. The stem is deep blue, with hair and no lichen on stem. The stem contains much water, is soft and white inside. The sheaves of bamboo shoot remain on the stem.
- "Medium": bamboos aged 2-3 years for *Nua*, *Vau*, *Lo o*; 3-4 years for *Luong*, *Dien*, and *Tre*. There are no sheaves on the stem and dense branches distribute mainly on the top of the stem. The colour of stem and main branch skin is deep blue mixed with brownish-yellow and there is spotted lichen on the stem.
- "Old": bamboos aged 3 years or more for *Nua*, *Vau*, *Lo o* and over 5 years or more for *Luong*, *Dien*, and *Tre*. The leaves are light blue and stems are bluish-yellow or spotted whitish-grey caused by strong development of lichen (70-80 %) and the deep blue colour of the stem skin has almost disappeared.

The cut bamboos were then separated into three components of stem, branch and leaf. Each bamboo component sample was weighed.

Sampling for analysis

For EB and deciduous forests, samples from every sample tree underwent dry mass analysis and WD analysis. For dry mass analysis, components of bole, branch and foliage were sampled. The weight of bole and branch samples is 0.5-1.0 kg each and 0.2-0.5 kg for samples of foliage. The samples for WD analysis were sampled from the four position of the bole of; stump level, 1/4 position of tree length, 1/2 position of tree length and 3/4 position of tree length. At every sampling position, one wood disc with thickness of 5-10 cm was taken as a sample. In case of big trees, the radial wood disc was taken.

For bamboo forests, samples for dry biomass analysis were taken from 75 out of 138 sample bamboo stems. The stem samples were taken at four different positions on the stem. The sampling positions are at stump level, 1/4 position of stem length, 1/2 position of stem length and at 3/4 position of stem length. The weight taken for dry mass analysis is 0.5-1.0 kg for every stem sample; weight of each branch sample is 0.5-0.8 kg and weight of each foliage sample is 0.2-0.5 kg.

All samples then were put into plastic bags and marked with labels. The information labeled on samples included: sample plot code, code of sample tree and sample name. The fresh weights of samples were measured accurately with use of a chemical scale with accuracy of 0.01 g. All samples were immediately sent to the Laboratory of RCFEE for further analysis.

2.2.2 Laboratory measurements

The samples were dried at 105^0C until they reached constant weight. Then, the dry-weight of samples were weighed using a chemical scale with accuracy of 0.01 g. Finally, the fresh and dry-weights of the samples were used to determine coefficient of dry/fresh biomass which was then used to calculate dry biomass of each tree component (bole, branches and foliage) of the sample trees from its fresh biomass.

Basic wood densities of all wood discs are determined at the moisture content of 0%. Wood density measurements methodology followed the National standard TCVN 8048-2: 2009. The wood volume was determined using the water displacement method with prism shaped and minimum sized: 20 x 20 x 25 mm subsamples. Wood densities was then calculated with the following formula:

$$SWD = \frac{SDW}{SV}$$

Where: *SWD* is the wood density of the sample in g/cm^3; *SDW* is the dry weight of sample cube and *SV* is the volume of sample cube.

2.2.3 Other variables

No volume measurement have been done in this study.

According to IPCC 2003, BEF is – when used to calculate aboveground biomass of forests – the ratio of aboveground oven-dry biomass of trees to oven-dry biomass of the commecial volume, dimensionless. The biomass of commercial volume can be calculated as commercial volume times wood density or directly measured as the biomass of tree bole. In this study the formula used is:

$$BEF = \frac{AGB_{total}}{AGB_{stem}}$$

2.3 Model fitting and selection

2.3.1 Data processing and regression analysis

All data collected in the field measurement were analyzed using Microsoft Excel for descriptive statistics including, mean, max and min values; standard deviation, N-DBH and N-G distribution. Statistical Package for Social Science (SPSS) was used to analyze regression for development of allometric equations for individual tree biomass estimation. The regression analysis was tested in forms of linear and non-linear. The variables used to predict biomass are DBH, H and WD. The general relationship form between biomass (y) and predictors (DBH, H, and WD) considered are:

- y = f (DBH)
- y = f (DBH, H)
- y = f (DBH, H, WD)

Criteria for selection of optimal allometric equations are:

- The highest value of coefficient of determination (R^2);
- Significances of t-test and F-test < 0.05;
- The smallest value of Akaike Information criterion (AIC);
- The smallest value of Correction Factor (CF);
- Validation of the hypothesis on residuals: The deviation of the predicted versus measured biomass were measured for chosen optimal allometric equations to validate the performance of the equations; then quantile-quantile plot was applied to check the hypothesis on the equation’s residuals. The average deviation was computed from the absolute difference between predicted and observed dry-weight and expressed as the percentage of observed dry-weight, then all deviations were averaged (Brand and Smith, 1985; Cairns et al., 2003; Chave et al., 2005; Nelson et al., 1999). The equation to calculate average deviation is shown in Equation (1). The deviation was calculated after the prediction was back-transformed to the unit values and corrected using CF. The average deviation has been calculated as follows:

$$\bar{S}\% = \frac{100}{n}\sum_{1}^{n}\frac{|(\widehat{Y_i} - Y_i)|}{Y_i}$$

where, $\bar{S}$ is the average deviation, Y_i = the observed dry weight, $\widehat{Y_i}$= the predicted dry weight, n = number of observations.

In addition, the correction coefficient recommended by Baskerville (1972) was used to correct estimates generated from logarithm transformation that was implemented prior to the development of allometric equations.

To correct the equation in the form of: $\ln(y) = b_0 + b_1 * \ln(x)$), the following correction factor (Baskerville factor - BF) should be estimated:

BF = (Standard Errors of Estimates) ^2/2 = Mean squared error/2

The corrected equation using BF will take the following form:

$Y = e$^(b_0 + (Mean squared error/2) + $b_1 * \ln(x)$)

3 RESULTS FOR EVERGREEN BROADLEAF (EB) FORESTS

3.1 Result 1: Forest and trees characteristics

3.1.1 Forest characteristics: species composition and forest structure

Species composition

The plant composition of survived plots were of 42 plant families, 64 genus and 85 tree species (Annex 1). The Fagaceae family has the largest number of species of eight; followed by the Lauraceae family of seven; the Clusiaceae family has six; and there are between one to five species for the remaining families (Annex 2).

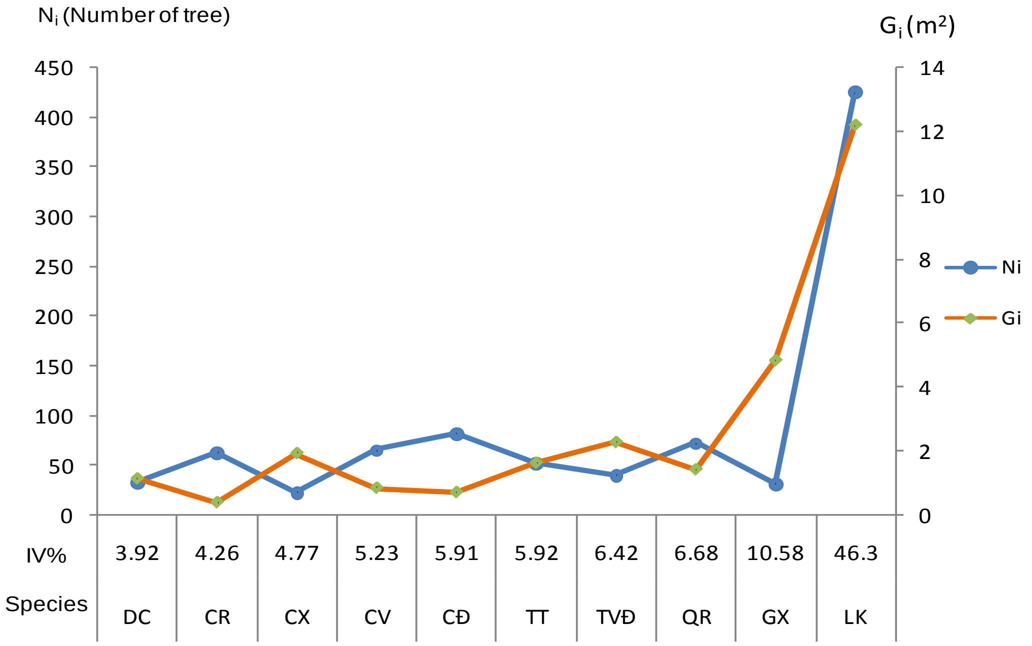
The estimated standing wood volume of the sampled EB forests was 370 m^3/ha and 225.8 m^3/ha. The tree species composition of EB forests is rather complex. Out of 85 species, there are six species with IV index higher than 5%. These species are *Michelia mediocris*, *Cinamomum iners, Syzygium zeylanicum, Syzygium wightianum, Garruga pierrei* and *Gonocaryum lobbianum*. *Michelia mediocris* had the largest wood volume of approximately 65.4m^3/ha, accounting for 21.93% of total standing wood volume, followed by *Syzygium zeylanicum,* with 23.9 m^3/ha, accounting for 8.01%. The species with the lowest wood volume is *Gonocaryum lobbianum,* with 4.2m^3/ha, accounting for 1.42% (Table 3).

Table 3 Tree number (N), total basal area (G) and IV index of EB forests

#	Species name	N **(tree/ha)**	N **(%)**	G **(m^2/ha)**	G **(%)**	IV **(%)**
1	*Michelia mediocris* (GX)	31	3.5	4.8	17.66	10.6
2	*Cinamomum iners* (QR)	72	8.2	1.4	5.20	6.7
3	*Syzygium zeylanicum* (TVD)	40	4.5	2.3	8.31	6.4
4	*Syzygium wightianum* (TT)	52	5.9	1.6	5.95	5.9
5	*Garruga pierrei* (CD)	82	9.2	0.7	2.60	5.9

6	*Gonocaryum lobbianum* (CV)	65	7.4	0.8	3.09	5.2
7	*Schima superba* (CX)	22	2.5	1.9	7.05	4.8
8	*Camellia assamica* (CR)	63	7.1	0.4	1.45	4.3
9	*Lithocarpus fenestratus* (DC)	33	3.7	1.1	4.16	3.9
Total (9 dominant species)		459	51.9	15.2	55.5	53.7
Other 76 species (LK), IV < 5%		425	48.1	12.2	44.5	46.3
Total per ha		883	100	27	100	100

The IV value of tree species in EB forests are significantly different (Figure 2). Species with high value of IV, for example *Michelia mediocris* (GX), *Syzygium zeylanicum* (TVD), recorded only a few numbers of tree individuals (31 trees/ha for GX, 40 trees/ha for TVD). However, other species such as *Garruga pierrei*, *Gonocaryum lobbianum* and *Camellia assamica* that have lower value of IV, recorded greater numbers of tree individuals. This can be explained by the fact that during the logging of the forest the big sized species of GX and TVD were harvested and were replaced by pioneer species. Consequently, the species with large individual tree occurrence but small in size (e.g. *Gonocaryum lobbianum*, *Garruga pierrei, Camellia assamica*) become the successional dominant species.[2]



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[2] According to Thai Van Trung (1978), the dominant trees species forming dominant plant groups in EB forests are *Michelia mediocris* (GX)*, Cinamomum iners* (QR)*, Syzygium zeylanicum* (TVD)*, Syzygium wightianum* (TT)*, Garruga pierrei* (CD)*, Gonocaryum lobbianum* (CV)*, Schima superba* (CX)*, Camellia assamica* (CR), and *Lithocarpus fenestratus* (DC). The species composition formula is: 9.66 GX: 4.55 TVD: 3.85 CX: 3.25 TT: 33.38 LK.

Figure 2 N-G distribution of dominant tree species by IV(%) index in EB forests

Forest structure

The observed N-DBH distribution tends to decline with increase in DBH size (Figure 3). Most of tree species occur most frequently in the DBH class of 5-15 cm; occurrence quickly reduces in the next DBH class of 15-25 cm. For trees with DBH greater than 35 cm, numbers of individual trees gradually reduces with the largest class having the least numbers of trees.

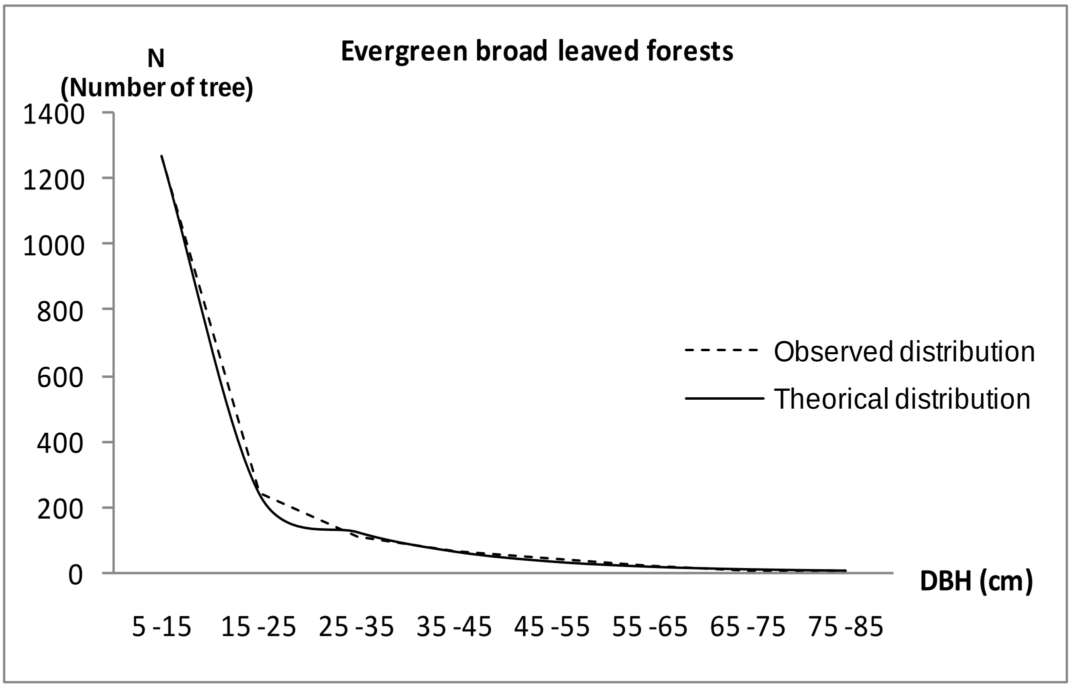


Figure 3 Observed and theatrical distribution of N-DBH for EB forests

The relationship between N (number of trees), G (total basal area) and DBH is described as G being a harmonized indicator formed by DBH and N. G is a condensed factor showing the denseness of the forests by horizontal view. To better understand the forest structure of the site, the distribution of N and G by DBH class was studied (Table 4).

Table 4 Observed distribution of tree number and basal area by DHB class of EB forests

DBH class (cm)	N_i (tree/ha)	N_i (%)	G_i (m^2/ha)	G_i (%)
5-15	1,269	72.0	8.0	14.7
15-25	244	13.9	7.0	12.8
25-35	107	6.1	7.6	13.9
35-45	62	3.5	7.9	14.5
45-55	45	2.6	8.7	15.9
55-65	24	1.4	6.9	12.6
65-75	9	0.5	3.5	6.5
75-85	2	0.1	4.9	9.0

Total	1,762	100	54.7	100

The results of the observed distribution of N-G-DBH indicated that the N-DBH distribution follows a declining trend, with the largest numbers of trees distributed in the DBH class of 5–15 cm and the number of trees reduces with increase in DBH class size. Unlike the N-DBH distribution, the observed distribution of G-DBH did not indicate any clear trends. The G-DBH distribution increases and/or decreases in DBH classes 5-25 cm and 65-85 cm. For the DBH class 25-65 cm, the G-DBH distribution is skewed to the right. The largest G value is observed in DBH class 45-55 cm (Figure 4).

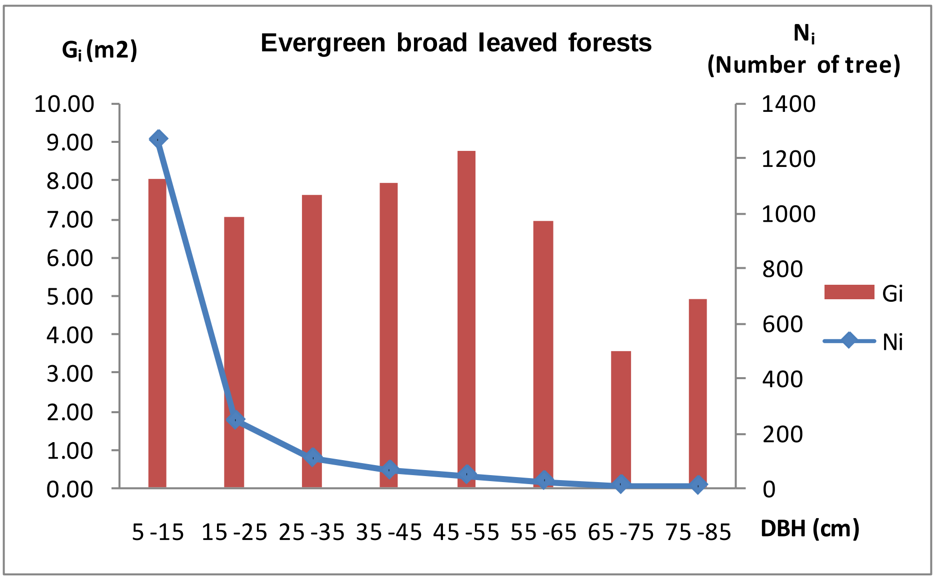


Figure 4 Observed distribution of tree number (N) and basal area (G) by DBH class of EB forests

The N-G-DBH distribution in EB forests can be explained by the competition processes for light, nutrients and space during the growing period leading to the decline of some species. The higher number of trees indicates greater competitiveness of a species. This process often takes place for plants in the forest floor layer; the more competitive plants are normally those smaller in size and frequent in number. Consequently, the number of trees decreases with increase in DBH (rule of N-DBH distribution). In the small DBH class of 5-25 cm, the number of trees decreases quickly and for larger DBH classes with low tree density, the number of trees reduces slowly.

For G-DBH distribution, there is no rule because G is a harmonized factor of DBH and tree density factors. The increase or decrease in G in any DBH class is normally caused by silvicultural practices such as thinning and selective logging. If the G of the thinned trees (i.e. G to be removed from the forest) is greater than total increment of G of remaining trees, then the G value of that DBH class will be reduced (such as in the DBH class 55-75 cm in this study). Conversely, if the increment of G is greater than G removed, then the G of that DBH class will increase though the number of trees is reduced (such as in the DBH class 25-55 cm in this study).

The distribution of N-G-DBH indicates that, with increase in DBH size, the number of trees does not increase as with G. For small DBH classes, there are a large number of trees, but their G accounts for a small portion. For example, in DBH class 5-25 cm, although the number of trees accounts for 85.6% of total trees, G is estimated at 27.5% of total G; and the remaining number of trees with DBH over 25 cm occupies over 70% of total G.

3.1.2 Relation between H and diameter

The relation between tree height and diameter at breast height have not been studied in this study.

3.1.3 Biomass of sample trees

In the study, biomass of 115 sample trees was measured. DBH of sample trees ranged between 6.1-73.8 cm, and for H, between 6.7-43.8 m. All felled sample trees belong to 18 tree species. Dry mass samples of bole, branch and foliage taken from 115 sample trees were analyzed. The total number of samples for dry mass analysis was 342, consisting of 115 bole samples, 115 branch samples and 114 foliage samples. The results of dry mass analysis indicated that the ratio of dry/fresh mass is highest for boles, with mean value of 0.58±0.037 (value range 0.53–0.631); followed by branches, with mean value 0.52±0.026 (value range 0.49–0.56); and the lowest for foliage, with mean value of 0.43 ± 0.042 (value range 0.32–0.47) (Table 5 and Annex 4).

Table 5 Ratio of dry mass to fresh mass of sample trees in EB forests

Local name	Scientific name	No. of sample trees	Dry & fresh-mass ratio		
			bole	branch	foliage
Dẻ cau	*Lithocarpus fenestratus*	16	0.63	0.55	0.47
Trâm vỏ đỏ	*Syzygium zeylanicum*	16	0.59	0.55	0.42
Dẻ Bắc Giang	*Lithocarpus bacgiangensis*	15	0.64	0.53	0.47
Giổi xanh	*Michelia mediocris*	15	0.54	0.49	0.39
Trâm trắng	*Syzygium wightianum*	14	0.59	0.52	0.44
Chò xót	*Schima superb*	9	0.53	0.47	0.41
Cóc đá	*Garruga pierrei*	8	0.64	0.52	0.38
Quế rừng	*Cinamomum iners*	6	0.59	0.56	0.44
Gội	*Aglaia korthalsii*	5	0.58	0.52	0.32
Others	Sp	10	0.55	0.52	0.41
Mean			0.58	0.52	0.43
Standard deviation			0.37	0.026	0.042

The results indicated that the ratio of dry/fresh mass of different tree species varies greatly. Ratio of dry/fresh mass was highest for *Lithocarpus bacgiangensis*, with mean value of 0.64. The lowest value was for *Michelia mediocris*, with mean value of 0.54. For branch, the ratio of dry/fresh mass was the highest for *Cinamomum iners*, with ratio of 0.56; and lowest with 0.47 for *Schima superb*. For foliage, the ratio of dry/fresh mass was consistently lower than that of bole and branch samples among all species. The species with highest ratio of dry mass to fresh mass for foliage component was *Lithocarpus bacgiangensis* (0.47) and the lowest was *Aglaia korthalsii* (0.32).

Analysis of biomass structure by components of bole, branch and foliage showed that there is a significant difference between biomass of components depending on tree size. However, a common trend is for the bole biomass to account for the biggest share, followed by branch and foliage.

Average share of bole biomass to the total biomass of the three components is 77.6 ± 8.8% (value range 69.3–84.8%). The average branch biomass ratio is 18.4 ± 8.1 (value range 14.0–27.2%); and average biomass of foliage is 3.9 ± 4.7% (value range 1.8–7.1%) (Table 6).

Table 6 Mean biomass structure by tree components for EB forests

Local name	Scientific name of species	n	Bole biomass		Branch biomass		Foliage biomass	
			%	STD	%	STD	%	STD
Dẻ cau	*Lithocarpus fenestratus*	16	77.02	7.8	17.81	7.0	5.17	4.2
Trâm vỏ đỏ	*Syzygium zeylanicum*	16	79.80	6.6	17.02	6.7	3.17	2.9
Dẻ Bắc Giang	*Lithocarpus bacgiangensis*	15	74.44	13.1	18.42	11.5	7.14	10.0
Giổi xanh	*Michelia aff. mediocris*	15	78.61	5.4	18.86	5.5	2.54	0.8
Trâm trắng	*Syzygium wightianum*	14	76.46	7.7	20.38	8.1	3.15	3.6
Chò xót	*Schima superba*	10	84.83	6.3	13.28	6.0	1.88	1.2
Cóc đá	*Garruga pierrei*	8	80.60	8.9	14.09	5.4	5.31	4.8
Quế rừng	*Cinamomum iners*	6	70.74	10.7	25.24	10.0	4.02	2.4
Gội	*Aglaia korthalsii*	4	69.35	5.2	27.20	4.7	3.44	1.5
Others[3]	Sp	11	77.59	8.8	19.51	8.6	2.91	1.9
Total/Mean		115	77.60	8.8	18.45	8.1	3.95	4.7

Analysis of biomass structure by DBH class also found that there is a small change in biomass by DBH class. The average bole biomass is 77.0 ± 2.86. % (value range 71.8–81.0%); branch biomass varies greatly, with average biomass of 19.8±3.4% (value range 15.6–26.4%); and foliage biomass tends to decrease with increase in DBH size. The average biomass portion of branch is 3.2±2.0% (value range 1.6-8.0%) (Table 7).

Table 7 Mean biomass structure by DBH class for EB forests

DBH class (cm)	n	Average percentage of dry mass (%)		
		Bole	Branch	Foliage
5-15	23	75.7	16.3	8.0
15-25	21	81.0	15.6	3.4
25-35	22	77.5	20.0	2.5
35-45	22	77.4	20.0	2.6
45-55	11	75.6	22.0	2.5
55-65	9	80.2	18.2	1.6

---

[3] *Gonocaryum lobbianum*, *Lophopetalum wightianum*, *Alstonia angustifolia*, *Ilex chevalieri*, *Ormosia pinnata*, *Barringtonia pauciflora* and *Swintonia floribunda.*

65-75	7	71.8	26.4	1.7
Mean (%)		77.0	19.8	3.2
Standard deviation		2.86	3.4	2.0

3.1.4 Wood density analysis

Analysis of 456 samples for wood density (WD) of 114 sample trees of 18 species indicated that the value of WD changes considerably among species. The mean value of WD for all 18 studied species is 0.72 ±0.13 g/cm^3 (value range 0.39-0.0.98 g/cm^3); the greatest mean value is 0.981 g/cm^3 and the smallest mean value is 0.393 g/cm^3 (Table 8 and Annex 9).

Table 8 Summary of WD (g/cm^3) of sample trees for EB forests. The values are based on the average of 4 wood density measurement per tree.

			Wood density (g/cm^3)			
Local name	Scientific Name	n	Average	Stdev	Min	Max
Bá khía	Lophopetalum wightianum	1	0.52	0.00	0.52	0.52
Chiếc tam lang	Barringtonia pauciflora	1	0.71	0.00	0.71	0.71
Chò xót	Schima wallichii	10	0.67	0.06	0.57	0.78
Cóc đá	Garruga pierrei	8	0.69	0.07	0.60	0.80
Cồng trắng	Calophylum dryobalannoides	1	0.69	0.00	0.69	0.69
Cuống vàng	Gonocaryum lobbianum	2	0.78	0.02	0.77	0.80
Dẻ Bắc Giang	Lithocarpus bacgiangensis	14	0.85	0.11	0.57	0.96
Dẻ cau	Lithocarpus fenestratus	16	0.81	0.14	0.51	0.96
Giổi xanh	Michelia mediocris	15	0.56	0.07	0.39	0.66
Gội	Aglaia korthalsii	4	0.67	0.09	0.57	0.76
Gội tía	Amoora gigantea	1	0.76	0.00	0.76	0.76
Mo cua la nho	Alstonia angustifolia	1	0.45	0.00	0.45	0.45
Nhựa ruồi	Ilex chevalieri	1	0.53	0.00	0.53	0.53
Quế rừng	Cinamomum iners	6	0.70	0.17	0.46	0.98
Ràng ràng	Ormosia pinnata	1	0.64	0.00	0.64	0.64
Trâm trắng	Syzygium wightianum	14	0.75	0.07	0.64	0.88
Trâm vỏ đỏ	Syzygium zeylanicum	16	0.76	0.07	0.64	0.90
Vạng trứng	Endospermum chinense	1	0.44	0.00	0.44	0.44
Xuân Thôn	Swintonia floribunda	1	0.75	0.00	0.75	0.75
Global results		114	0.72	0.13	0.39	0.98

3.2 Result 2: Modeling of the stem volume

As the volume has not been measured in this study, volume modeling has not been done.

3.3 Result 3: Modeling of Aboveground biomass

3.3.1 Modeling per tree compartments

The study focused on the modeling of total aboveground biomass. Modeling of biomass per tree compartment has not been developed.

3.3.2 Modeling of total aboveground biomass

As the first step for selecting regression models for allometric equations development, graphic exploration of dependent biomass values and independent variables such as DBH, H, and WD was undertaken using SPSS software, to predict relationships. Models indicating close to normal distribution with the highest coefficient of determination were chosen to develop allometric equations for biomass estimation. The results indicate the power model as the best choice for expressing the relationships between AGB and DBH, H and WD because of their high coefficients of determination and their predicted values close to a normal distribution (Annex 11). The power model is as follows:

$B = a*X^b$ Equation (1)

where, B = Biomass (kg) of tree components, a and b are constants, X = DBH (cm), $DBH^2.H$; and DBH^2H*WD

According to Chavel et al., (2005), AGB should be estimated using WD, G and H. An equation was developed following this:

$AGB = F \times (WD \times (\frac{\pi DBH^2}{4}) \times H)$ Equation (2)

where: F = Form factor

Logarithm transformations, routinely used in dimension analysis studies (Sprugel, 1983), were employed to fit allometric equations to sample data. Regression models, transformed into linear and non-linear models, as follows;

Linear models:

$Ln(B) = \gamma + a*Ln(DBH)$ Model (1)

where, γ and a: parameters; B: Biomass of tree components and AGB

$Ln(B) = \gamma + a*Ln(DBH^2*H)$ Model (2)

where, γ, a, b and c: parameters; B: Biomass of tree components and AGB

$Ln(AGB) = \gamma + a*Ln(DBH^2*H*WD)$ Model (3)

where, γ and a: parameters

Non-linear models:

$Ln(AGB) = \gamma + a*Ln(DBH) + b*(LnH) + c*Ln(WD)$ Model (4)

where, γ, a, b, and c: parameters

$Ln(AGB) = \gamma + a*Ln(DBH) + b*(Ln(DBH))^2 + c*(Ln(DBH))^3 + d*Ln(WD)$ Model (5)

where, γ, a, b, c and d: parameters

$Ln(AGB) = \gamma + a*Ln(DBH) + b*(Ln(DBH))^2 + c*(Ln(DBH))^3 + Ln(WD)$ Model (6)

where, γ, a, b and c: parameters (d=1)

$Ln(AGB) = \gamma + a*Ln(DBH) + Ln(WD)$ Model (7)
where γ, a : parameters (b, c = 0; d = 1)

Linear regression equations

Three linear allometric models were developed for tree biomass and tree measurement variables including DBH, H, and WD. Model (1) expresses the relationship between biomass (for tree components of bole, branch and foliage and AGB) with variable of DBH, and Model (2) expresses the relationship between biomass (for tree components and AGB), with variables DBH and H; Model (3) expresses the relationship between AGB with variables DBH, H and WD. The developed allometric equations were based on data of 105 sample trees.

The F-test results show that all equations developed from Model (1) and (2) are statistically valid (i.e., F-values are less than an alpha of 0.05). In addition, the correlation coefficients of these equations are close to 1, implying that there are close relationships between biomass and DBH (i.e., $R^2 = 0.75 \div 0.96$). The values of AIC and CF of these equations are very small, especially for the equations relating AGB to DBH (i.e., CF = 1.055 and AIC = -233.47) and AGB to DBH and H (CF = 1.049 and AIC = -245.80) (Table 9). The deviation between measured and predicted variables may be not significant for these equations. Another trend observed is AIC and CF values to decrease as the coefficients of determination increase for equations following Model (1) and (2). The equations to estimate foliage, branch and bole biomass have high values of AIC and CF thus are normally not reliable and difficult for further application; these were not selected.

Similarly, DBH, H and WD were used as variables in Model (3) to estimate AGB, following the recommendation of Dawnkins (1961) and Brown et al., (1989). All equations developed from Model (3) have coefficients of determination approaching 1 and low values of CF and AIC parameters (i.e., CF = 1.02 and AIC = 321.09). Compared to equations developed from Model (1) and (2), these equations are statistically preferred in the selection of the optimal equations to estimate AGB. The developed allometric equations following Models (1), (2), and (3) are as follows:

Equations following Model (1):

$Ln(Bf) = -2.295 + 1.594*Ln(DBH)$ or $Bf = 0.10* DBH^{1.594}$ Equation (1.1)

$Ln(Bb) = -3.925 + 2.611*Ln(DBH)$ or $Bb = 0.02*DBH^{2.61}$ Equation (1.2)

$Ln(Bs) = -1.805 + 2.395*Ln(DBH)$ or $Bs = 0.164*DBH^{2.395}$ Equation (1.3)

$Ln(AGB) = - 1.518 + 2.387*Ln(DBH)$ or $AGB = 0.222*DBH^{2.387}$ Equation (1.4)

Equations following Model (2):

$Ln(Bf) = 2.668 + 0.634*Ln(DBH^2*H)$ or $Bf = 14.41*(DBH^2*H)^{0.634}$ Equation (2.1)

$Ln(Bb) = 4.222 + 1.033*Ln(DBH^2*H)$ or $Bb = 68.17*(DBH^2*H)^{1.033}$ Equation (2.2)

$Ln(Bs) = 5.636 + 0.960*Ln(DBH^2*H)$ or $Bs = 280.34*Ln(DBH^2*H)^{0.96}$ Equation (2.3)

$Ln(AGB) = 5.903 + 0.97*Log(DBH^2*H)$ or $AGB = 366.13*(DBH^2*H)^{0.97}$ Equation (2.4)

Equation following Model (3):

$$Ln(AGB) = 6.201 + 0.97*Ln(DBH^{2}*H*WD) \text{ or } AGB = 493.24*(DBH^{2}*H*WD)^{0.}$$

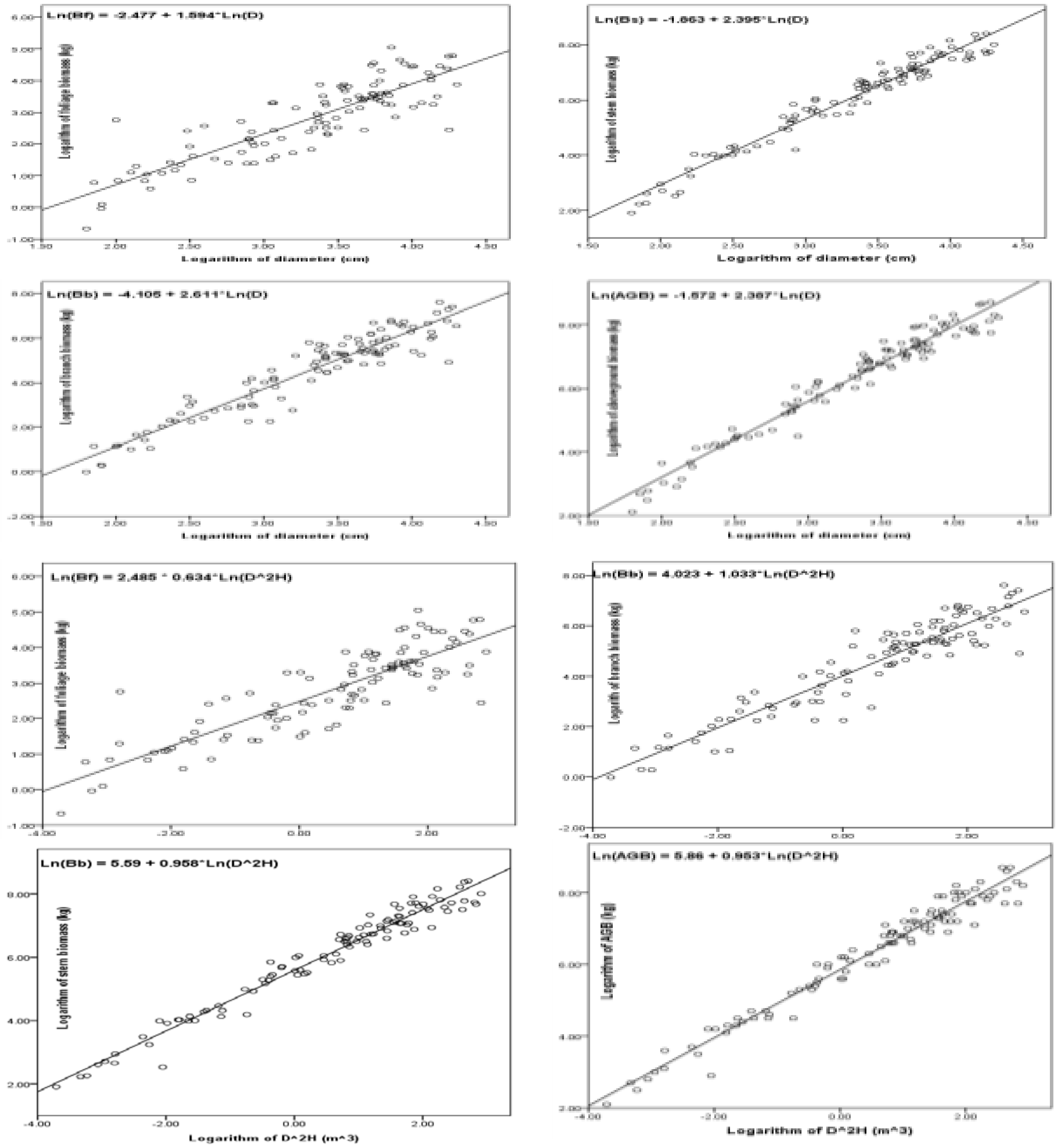
Equation (3.1)

Table 9 Outputs of linear regression analysis for biomass estimation for EB forests

Model & predicted variable	Equation number	n	Interval of variables			γ	BF*	a	R^2	Sig.	CF	AIC
			DBH	H	WD							
Model (1)												
Foliage biomass (Bf)	(1.1)	105	6.05–73.82	NA	NA	-2.477	0.182	1.594	0.75	0.000	1.197	- 106.23
Branch biomass (Bb)	(1.2)					-4.105	0.18	2.611	0.89	0.000	1.194	-107.39
Bole biomass (Bs)	(1.3)					-1.863	0.058	2.395	0.96	0.000	1.059	-225.77
AGB	(1.4)					-1.572	0.054	2.387	0.96	0.000	1.055	-233.47
Model (2)												
Foliage biomass (Bf)	(2.1)	105	6.05–73.82	6.70–43.79	NA	2.485	0.183	0.634	0.75	0.000	1.198	-105.62
Branch biomass (Bb)	(2.2)					4.023	0.199	1.033	0.88	0.000	1.218	-96.67
Bole biomass (Bs)	(2.3)					5.59	0.046	0.958	0.96	0.000	1.047	-249.79
AGB	(2.4)					5.855	0.048	0.97	0.96	0.000	1.049	-245.80
Model (3)												
AGB	(3.1)	105	6.05–73.82	6.70–43.79	0.39–0.98	6.178	0.023	0.97	0.98	0.000	1.02	-321.09

Comparison of developed equations show that the Equation (3.1) with three variables of DBH, H and WD presents the lowest AIC value, thus is preferred for estimating AGB for EB forests. The CF value of Equation (3.1) is also lower than those of other developed equations (i.e., equation (1.4) and (2.4)), implying that Equation (3.1) is more reliable. There are no significant differences in coefficients of determination of developed equations; therefore, the coefficients cannot serve as an important factor in the comparison of the equations.

The above analysis indicates that Equation (3.1) is preferable to equation (1.4) and (2.4) in terms of accuracy and distribution of observed values (i.e., approach to normal distribution) (Figure 5). However, Equations (1.4) and (2.4) have the advantage of having fewer variables thus more simple to measure. The three equations were statistically analyzed using given biomass data for validation. The equation with the smallest deviation between measured and predicted variables was selected as an optimal allometric relationship.



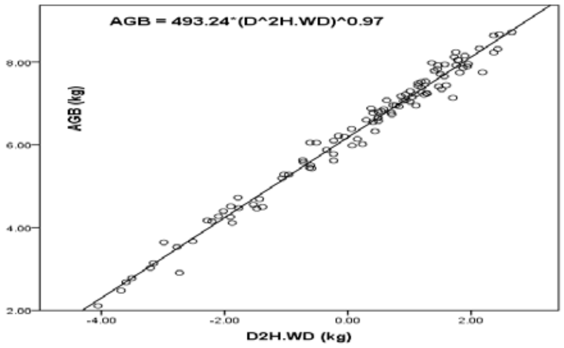


Figure 5 Linear regressions between biomass (of foliage, branch, bole, and AGB) and DBH, H and WD.

Non-linear regression equations

Ketterings et al., (2001) has shown that the inclusion of variables H and DBH in the power equation gives only a slight improvement in the fraction of variance explained by the model for a specific site; however, the incorporation may be important when comparing different sites. Evidently, tropical forest consists of various tree species with different WD, which may lead to different coefficients of the equations. Tanaka et al., (2009) points out that different WD values results in differences in biomass estimation using the equation developed by Brown (1997) and the equation in the study of Tanaka et al., (2009). Chave et al., (2005) points out that equations using WD as variable may improve accuracy.

Four non-linear equations relating AGB to variables DBH, H and WD for EB forests were developed.

Equation following Model (4):

$$\mathrm{Ln(AGB)} = -2.318 + 2.08*\mathrm{Ln(DBH)} + 0.71*\mathrm{Ln(H)} + 1.12*\mathrm{Ln(WD)} \quad \text{or}$$
$$\mathrm{AGB} = 0.098*\exp(2.08*\mathrm{Ln(DBH)} + 0.71*\mathrm{Ln(H)} + 1.12*\mathrm{Ln(WD)}) \qquad \text{Equation (4.1)}$$

Equation following Model (5):

$$\mathrm{Ln(AGB)} = -2.89 + 3.44*\mathrm{Ln(DBH)}-0.148*(\mathrm{Ln(DBH)})^2-0.003*(\mathrm{Ln(DBH)}^3+1.064*\mathrm{Ln(WD)} \quad \text{or}$$
$$\mathrm{AGB}=0.056*\exp(3.44*\mathrm{Ln(DBH)}-0.148*(\mathrm{Ln(DBH)})^2-0.003*(\mathrm{Ln(DBH)}^3+1.064*\mathrm{Ln(WD)}) \qquad \text{Equation (5.1)}$$

Equation following Model (6):

$$\mathrm{Ln(AGB)} = -2.362+3.35*\mathrm{Ln(DBH)}-0.112*(\mathrm{Ln(DBH)})^2 - 0.008(\mathrm{Ln(DBH)})^3 + \mathrm{Ln(WD)} \quad \text{or}$$
$$\mathrm{AGB} = \mathrm{WD}*\exp(-2.362+3.35*\mathrm{Ln(DBH)}-0.112*(\mathrm{Ln(DBH)})^2 - 0.008(\mathrm{Ln(DBH)})^3) \qquad \text{Equation (6.1)}$$

Equation following Model (7):

$$\mathrm{Ln(AGB)} = -1.332 + 2.43*\mathrm{Ln(DBH)} + \mathrm{Ln(WD)} \quad \text{or}$$
$$\mathrm{AGB} = \mathrm{WD}*\exp(-1.332 + 2.43*\mathrm{Ln(DBH)}) \qquad \text{Equation (7.1)}$$

Results derived from the F-test show that all equations are valid and have the same coefficients of determination. There is a negligible difference of CF values among the four equations. The lowest and highest values of CF belong to Equation (4.1) and Equation (7.1), respectively (i.e., 1.022 and 1.028). Unlike many of the linear equations mentioned above, the non-linear relationships show no significant differences in AIC values (value range -320.36 to -300.4). Differences in R^2 values are also negligible, thus cannot be used as a criterion to select the optimal equation. It is evident that equations with all three variables of DBH, H and WD are preferable to those only with WD and H (Table 10).

The statistical parameters indicate Equation (4.1), with small values of AIC and CF, may generate the highest accuracy in estimating AGB for EB forests (Table 10). In addition to using statistical coefficients for selecting the optimal allometric equation, Equation (4.1) was also validated by the comparasion between its predicted values and given biomass data with the other three non-linear equations. The equation that shows the smallest value of deviation is selected as the optimal allometric equation for AGB estimation.

Table 10 Outputs of non-linear regression analysis for biomass estimation for EB forests

Model	Equation number	n	Interval of variable			γ	BF*	a	b	c	d	R^2	Sig.	CF	AIC
			DBH	H	WD										
Model (4)															
	(4.1)	105	6.05–73.82	6.70–43.79	0.39–0.98	-2.34	0.022	2.08	0.71	1.12	NA	0.98	0.000	1.022	-320.36
Model (5)															
	(5.1)	105	6.05–73.82	6.70–43.79	0.39–0.98	-2.89		3.44	-0.148	-0.003	1.064	0.98	0.000	1.024	-307.84
Model (6)															
	(6.1)	105	6.05–73.82	NA	0.39–0.98	-2.836	0.024	3.35	-0.112	-0.008	1	0.98	0.000	1.025	-309.51
Model (7)															
	(7.1)	105	6.05–73.82	NA	0.39–0.98	-1.36	0.028	2.43	0	0	1	0.98	0.000	1.028	-300.43

* Baskerville Factor

Validation of equations

Validation was undertaken by comparing biomass estimations from the developed optimal equations with measured biomass from sample trees. Equation (3.1) was used to estimate the average deviation using given biomass data and predicted data generated from the selected equation. Ten sample trees were used for validation. Resutls show that the developed equations for have high accuracy for estimating biomass for EB forests. The average deviation between estimated biomass values from equations and measured biomass range between 14.17-18.10% (Table 11), and can be considered negligible. The equation using three variables of DBH, H and WD generated the lowest values of deviation (around 14%) (Table 11), and the residuals generated from measured biomass data and predicted values are also the smallest (Annex 12). Meanwhile, Equation (1.4) had the highest values of AIC and CF (ie., AIC=-233.47 and CF=1.055) among the four selected equations and with deviation value of apprixmaltely 17%.

In general, all selected equations are statistically valid to be used to estimate AGB of EB forests. However, noting that a greater number of variables considered implies higher costs and resource needs for measurement in field work, the use of both Equation (1.4) and Equation (4.1) are considered as most optimal equations, for estimating AGB of EB forests in the Central Highlands of Viet Nam.

Table 11 Validation of equations for biomass estimation of EB forests

Equation	$\widehat{Y_i}$ (kg)	Y_i (kg)	Average deviation (%)
Equation (1.4)	1,500.68	1,643.12	17.67
Equation (2.4)	1,500.68	1,613.62	18.10
Equation (3.1)	1,500.68	1,423.89	14.44
Equation (4.1)	1,500.68	1,452.84	14.17

3.3.3 Modeling of ABG for the main tree families and species

Not enough trees have been sampled in the main tree families and species to develop robust allometric equations.

3.3.4 Comparison with generic models

The average deviation of difference between the values estimated through the equation developed by Brown (1997) ($AGB = 0.1183*DBH^{2.530}$) and the final optimal equation with variable DBH developed in this study (Equation (1.4)) using data collected from 105 sample trees are 27.73% and 32.64%, respectively (Figure 6). Meanwhile, a comparison of values estimated by the equations developed by Chave (2005) (AGB = 0.0509*WD*D^2*H) and Equation (4.1) using variables of DBH, H and WD results in deviations of 19.13% and 18.80%, respectively (Figure 7). Compared with those in previously published studies, Equation (4.1) have nearly equivalent or negligibly higher accuracy in estimating AGB.

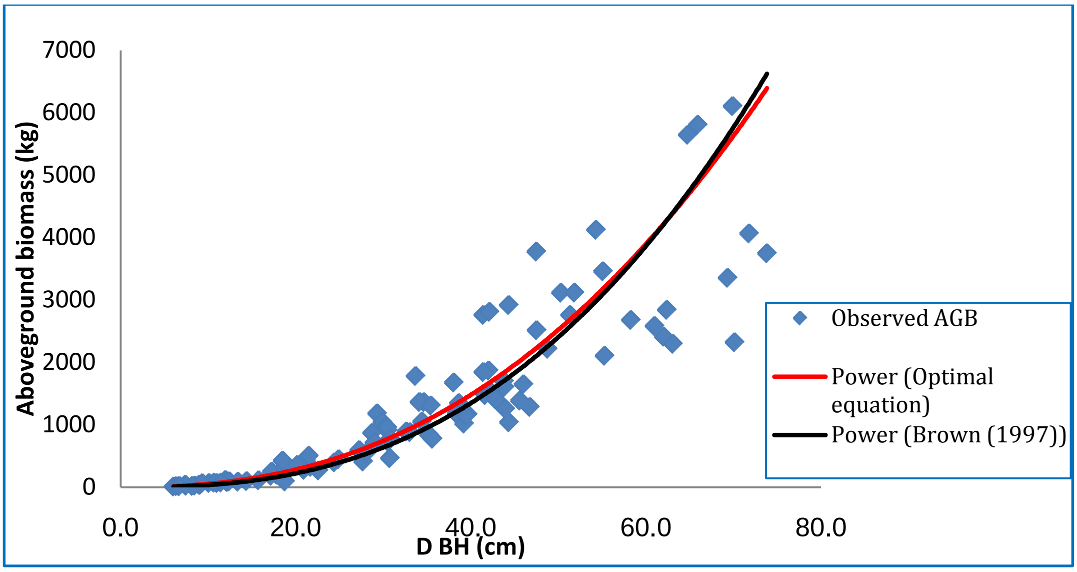


Figure 6 Comparison with the relationship developed by Brown (2001) between AGB and DBH of tropical moist forest trees.

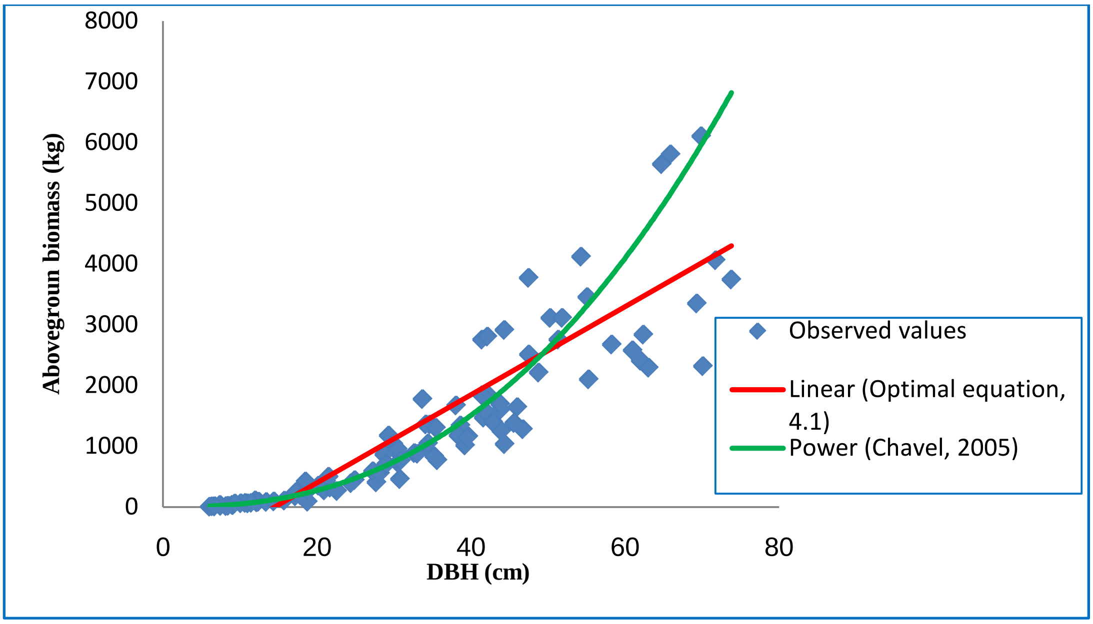


Figure 7 Comparison with the equation of Chave (2005) between AGB and DBH, H, and WD of tropical moist forest trees

3.4 Result 4: BEF (totalAGB/ABGstem)

The result for the 115 trees sampled in evergrenn beroadleave forest is a BEF average value of 1.31 ± 0.18. The minimal value is 1.1 and the maximal is 2.4.

4 RESULTS FOR DECIDUOUS FORESTS

4.1 Result 1: Forest and trees characteristics

4.1.1 Forest characteristics: species composition and forest structure

Species composition

In the plot survey for deciduous forests, trees from 16 plant families, 20 genus and 26 species were identified (Annex 3). Among the 16 plant families, the Diterocarpaceae family has the largest number of species, with three species, followed by the Ebenaceae family, the Combretaceae family and the Mimosaceae family with two species and the other families with one species each.

Unlike EB forests, the species composition of deciduous forests is simple, with only five dominant species of *Shorea obtusa* (Cà chít), *Shorea siamensis* (Cẩm liên), *Dipterocarpus intricatus* (Dầu lông), *Lithocarpus bacgiangensis* (Dẻ đá Bắc giang) and *Craibiodendron scleranthum* (Cáp mộc núi hòn) (Table 12).

Table 12 Number of trees (N), basal area (G), wood volume (M) and IV index of tree species in deciduous forests

ID	Species	N	N %	G (m^2)	G (%)	IV (%)	M (m^3)	M (%)
1	Shorea obtuse (CC)	239	32.6	5.50	34.9	33.7	26.97	34.2
2	Shorea siamensis (CL)	174	23.7	3.38	21.5	22.6	16.12	20.4
3	Dipterocarpus intricatus (DL)	128	17.4	1.41	9.0	13.2	4.65	5.9
4	Craibiodendron scleranthum (CM)	44	6.0	2.05	13.0	9.5	13.23	16.8
5	Lithocarpus bacgiangensis (DĐBG)	56	7.6	0.85	5.4	6.5	3.90	4.9
Total of above 5 dominant species		641	87.3	13.19	83.8	85.6	64.87	82.3
Other 21 species (LK), IV < 5%		93	12.7	2.55	16.2	14.4	14.00	17.7
Total per 1 ha		734	100	16	100	100	79	100

For deciduous forest, the estimated standing wood volume was about 65 m^3/ha. Among the dominant tree species groups, *Shorea obtusa* is the most dominant in terms of numbers of trees and standing wood volume (239 trees/ha, 26.97 m^3/ha or 34.2% of total standing wood volume), followed by *Shorea siamensis* (174 trees/ha, 16.12 m^3/ha or 20.4% of total standing wood volume) and the remaining is composed of different species (93 trees/ha, 14 m^3/ha or 17.7% of total standing wood volume).

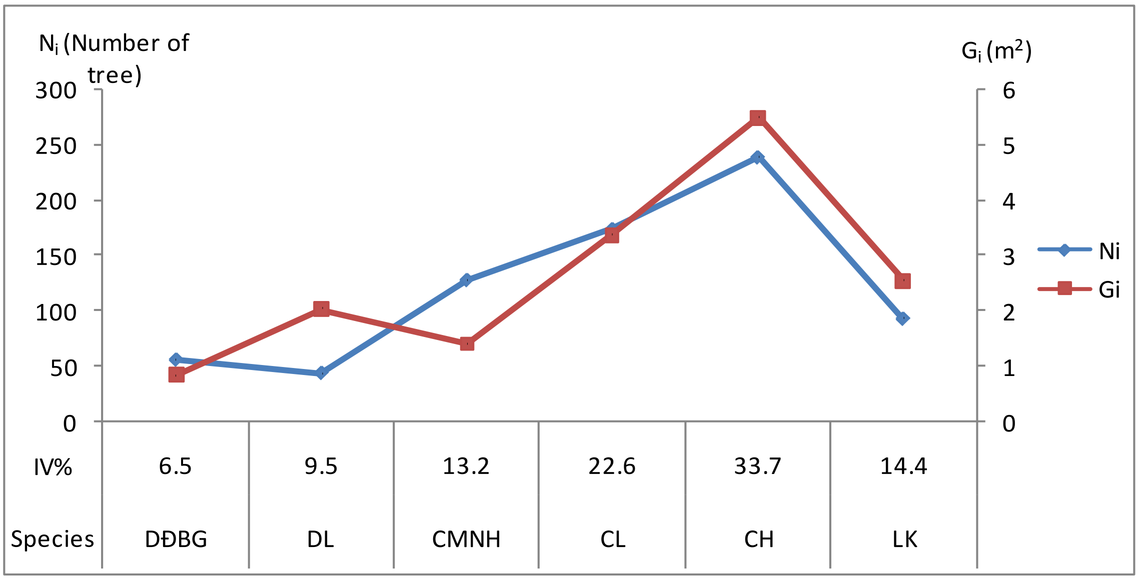


Figure 8 N-G distribution of dominant tree species by IV index in deciduous forests

The IV of *Shorea obtuse* and *Shorea siamensis* account for more than 50%.[4] The formula for species composition in the studied site is: 5.34CC + 3.38CL + 1.83DL + 1.41CM + 0.85DĐ + 2.55LK.

Forest structure

Distribution of N-DBH and N-G by DBH class

For N-DBH distribution in deciduous forests, a similar trend was observed as in EB forests; a declining distribution, with the greatest number of trees in DBH class 5-15 cm, and the number of trees gradually decreasing with increase in DBH size (Figure 9).

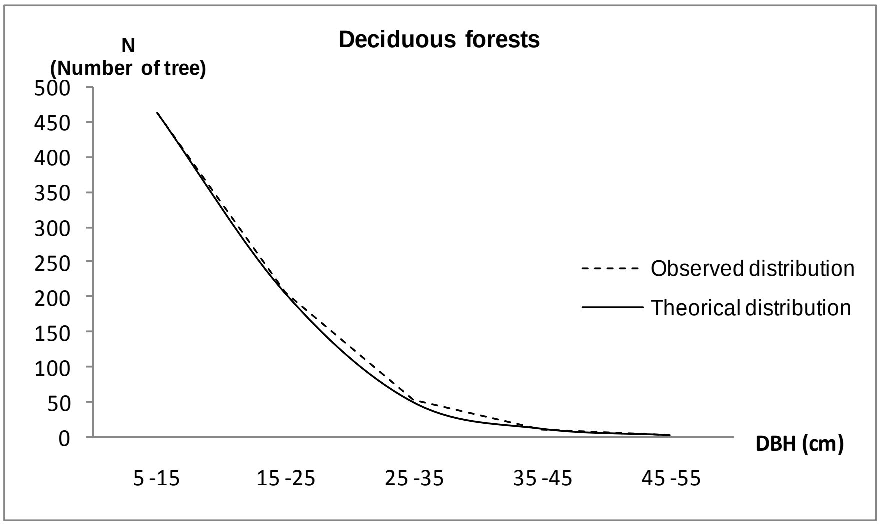


Figure 9 Observed and theoretical distribution of N-DBH for deciduous forest

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[4] According to the views of Thai Van Trung (1978), these two species are species that form dominant species group in deciduous forests.

Table 13 Observed distribution of N-G-DBH in deciduous forest

DBH class (cm)	N_i^{-}(tree/ha)	N_i%	G_i (m^2/ha)	G_i%
5-15	463	63.1	4.13	26.3
15-25	205	27.9	5.89	37.4
25-35	50	6.8	3.34	21.2
35-45	10	1.4	1.21	7.7
45-55	6	0.8	1.17	7.4
Total	734	100	15.74	100

The results indicate that there is a clear rule for N-G-DBH distribution (Table 13). The N-DBH distribution is a declining curve and the G-DBH distribution is skewed to the left, with the greatest G value in DBH class 15-25 cm, and for G to decline as DBH increases (Figure 10).

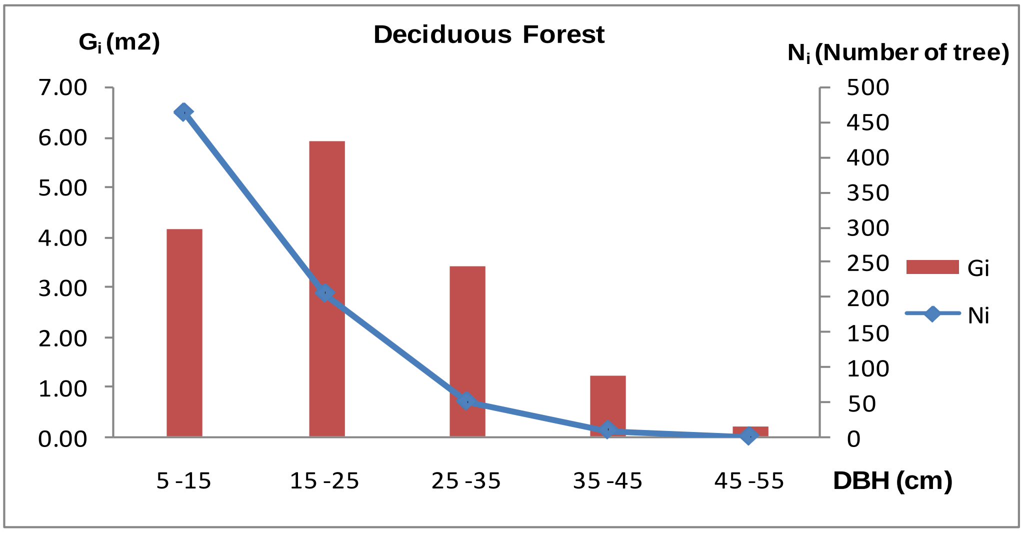

Figure 10 Observed distribution of N-G-DBH in deciduous forests

There is no clear trend for N-G-DBH. Within DBH class 5–25 cm, the N value accounts for 91.5% of total trees of the forests whereas, the G value accounts for 67.6% of total G of the plot. For the remaining DBH classes, total N is 8.5%, whereas G is 32.4% of total G of the plot.

4.1.2 Relation between H and diameter

The relation between tree height and DBH have not been developed in this study

4.1.3 Biomass of sample trees

Destructive measurement for estimation of biomass of deciduous forests was conducted for 68 sample trees, with DBH of 7.2–52.2 cm and H of 5.2–24 m. The sample trees for felling were selected randomly from 13 dominant tree species found, including typical species of *Dipterocarpus intricatus*, *Shorea obtuse*, *Shorea siamensis* and *Xylia xylocarpa*. The results of dry mass analysis for 204 samples taken from 68 sample trees (68 samples each for bole, branch and foliage) showed that the ratio of dry/fresh mass is highest for the bole, with mean value of 0.63 ± 0.24 (value range 0.52–0.67); followed by the branch with mean value of 0.48 ± 0.32 (value range 0.33–

0.52); and foliage has the lowest mean value of 0.38 ± 0.32 (value range 0.28–0.41) (Annex 5 and Table 14).

Table 14 Ratio of dry mass to fresh mass of sample trees by species

Local name	Scientific name of species	n	Ratio of Dry-Fresh mass		
			bole	branch	foliage
Cà chít	*Shorea obtuse*	24	0.65	0.50	0.39
Dầu lông	*Dipterocarpus intricatus*	12	0.61	0.47	0.40
Cẩm liên	*Shorea siamensis*	12	0.61	0.43	0.34
Căm xe	*Xylia xylocarpa*	1	0.59	0.47	0.35
Kơ nia	*Irvingia malayana*	1	0.52	0.33	0.28
Thanh mai	Sp	4	0.67	0.52	0.37
Thị rừng	*Diospyros sylvatica*	3	0.60	0.51	0.40
Xoài rừng	*Mangifera minitifolia*	3	0.61	0.46	0.41
Loài khác	Others[5]	8	0.61	0.44	0.32
Mean			0.61	0.46	0.36
Standard deviation			0.04	0.05	0.04

Analysis of biomass structure by tree components (bole, branch and foliage) indicate that biomass varies grealty among components depending on tree size and species. However, a general trend is that the bole accounts for the largest share of biomass among components, followed by branch and foliage. Mean biomass of bole accounts for 81.3 ± 1.0% (value range 60.1–84.0%); branch accounts for 16.2 ± 0.9% (value range 10.0–31.5%); and foliage is 2.4 ± 0.2% (value range 1.2-7.8%) (Table 15).

Table 15 Mean biomass structure of bole, branch and foliage by species

Local name	Scientific name	n	Bole biomass		Branch biomass		Foliage biomass	
			%	STD	%	STD	%	STD
Cà chít	*Shorea obtusa*	23	81.96	6.9	15.22	6.1	2.81	1.7
Dầu lông	*Dipterocarpus intricatus*	10	88.57	7.0	8.92	5.9	2.51	1.9
Cẩm liên	*Shorea siamensis*	10	81.91	6.8	13.89	6.1	4.20	2.2
Căm xe	*Xylia xylocarpa*	2	60.13	5.6	32.08	0.0	7.80	3.2
Kơ nia	*Irvingia malayana*	2	81.33	6.2	14.76	0.0	3.91	2.7
Thanh mai	*Sp*	4	85.97	3.7	11.16	4.5	2.87	1.1
Thị rừng	*Diospyros sylvatica*	3	62.72	5.0	30.64	2.0	6.64	5.3

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[5] *Leucaena leucocephala*, *Adina pilulifra*, *Lithocarpus bacgiangensis.*

Xoài rừng	*Mangifera minitifolia*	4	83.18	9.1	15.71	9.0	1.11	0.3
Loài khác	Others	10	76.78	12.2	18.61	11.2	4.61	2.9
Total/mean		68	81.25	9.6	15.31	8.4	3.44	2.5

Dry biomass structure by DBH class varies among components. The dry biomass of bole varies greatly between DBH classes, with an average rate of 80.54 ± 3.01% (value range 76.0–84.4%). However, the biomass of branch component changes only slightly between DBH classes, the mean value is 16.4 ± 2.4% (13.5-21.5%). Foliage biomass tends to decrease with increase in DBH. The mean value of foliage biomass is 3.0 ± 1.2% (2.1-5.3%) (Table 16).

Table 16 Average dry-biomass structure of bole, branch and foliage by DBH class

DBH class (cm)	n	Portion of dry biomass (%)		
		Bole	Branch	Foliage
5-15	17	78.3	16.5	5.3
15-25	17	82.5	14.5	2.9
25-35	19	84.4	13.5	2.1
35-45	10	81.5	16.3	2.2
45-55	5	76.0	21.5	2.5
Mean (%)		80.54	16.46	3.00
Standard deviation		3.01	2.76	1.18

4.1.4 Wood density analysis

Analysis of WD was conducted on 55 sample trees among the 68 felled samples. Total number of samples was 220, composed of 14 tree species. The analysis showed that there is a significant difference in WD within species. The mean value of WD was 0.5 ± 0.09 g/cm^3 (value range 0.65–1.03 g/cm^3) (Table 17 and Annex 10).

Table 17 Summary of WD (g/cm^3) of sample trees in deciduous forest. The calculations have been made on averages of 4 wood density per tree.

Local name	**Scientific name**	**Wood density (g/cm^3)**				
		n	Average	STDEV	Min	Max
Cà chít	Shorea obtusa	19	0.87	0.05	0.80	0.98
Cà gừng	ND	1	0.89	0.00	0.89	0.89
Cẩm liên	Shorea siamensis	9	0.84	0.08	0.72	0.92
Căm xe	Xylia xylocarpa	1	0.79	0.00	0.79	0.79
Dầu lông	Dipterocarpus intricatus	7	0.80	0.07	0.72	0.89
Dẻ Bắc Giang	Lithocarpus bacgiangensis	4	0.81	0.09	0.76	0.95
Gáo vàng	Adina pilulifra	1	0.68	0.00	0.68	0.68
Kơ nia	Irvingia malayana	1	0.88	0.00	0.88	0.88
Sắn ổi	ND	1	1.03	0.00	1.03	1.03

Thanh mai	ND	4	0.98	0.04	0.93	1.03
Thành ngạnh	Cratoxylum pruniflorum	1	0.80	0.00	0.80	0.80
Thị rừng	Diospyros sylvatica	3	0.81	0.05	0.78	0.87
Xoài rừng	Mangifera minitifolia	3	0.71	0.05	0.65	0.74
Global results		55	0.85	0.09	0.65	1.03

4.2 Result 2: Modeling of the stem volume

As the stem volume has not been measured in this study, the modeling has not been undertaken.

4.3 Result 3: Modeling of aboveground biomass

4.3.1 Modeling per tree compartments

The study focused on the modeling of total aboveground biomass, the modeling of biomass per tree compartment has not been undertaken.

4.3.2 Modeling of total aboveground biomass

Linear regression equations

The development of linear and non-linear equations for biomass estimation of deciduous forests followed the same procedures as for EB forests. Graphic exploration also indicated that observed values, following the power model were closest to a normal distribution (Annex 11). The power model was transformed into linear models by logarithm transformation of independent and dependent variables; equations were developed employing data of 60 sample trees (Table 18).

Developed equations are as follows:

Equations following Model (1):

$Ln(Bf) = -3.233 + 1.59*Ln(DBH)$ or $Bf = 0.10* DBH^{1.59}$ Equation (1.5)

$Ln(Bb) = -4.015 + 2.37*Ln(DBH)$ or $Bb = 0.02*DBH^{2.37}$ Equation (1.6)

$Ln(Bs) = -2.304 + 2.32*Ln(DBH)$ or $Bs = 0.10*DBH^{2.32}$ Equation (1.7)

$Ln(AGB) = - 1.934 + 2.31*Ln(DBH)$ or $AGB = 0.14*DBH^{2.31}$ Equation (1.8)

Equations following Model (2):

$Ln(Bf) = 2.036 + 0.60*Ln(DBH^2*H)$ or $Bf = 7.66*(DBH^2*H)^{0.60}$ Equation (2.5)

$Ln(Bb) = 3.826 + 0.88*Ln(DBH^2*H)$ or $Bb = 45.88*(DBH^2*H)^{0.88}$ Equation (2.6)

$Ln(Bs) = 5.459 + 0.90*Ln(DBH^2*H)$ or $Bs = 234.86*Ln(DBH^2*H)^{0.90}$ Equation (2.7)

$Ln(AGB) = 5.62 + 0.89*Log(DBH^2*H)$ or $AGB = 275.89*(DBH^2*H)^{0.89}$ Equation (2.8)

Equation following Model (3):

$Ln(AGB) = 5.808 + 0.88*Ln(DBH^2*H*WD)$or $AGB = 332.95*(DBH^2*H*WD)^{0.88}$

Equation (3.2)

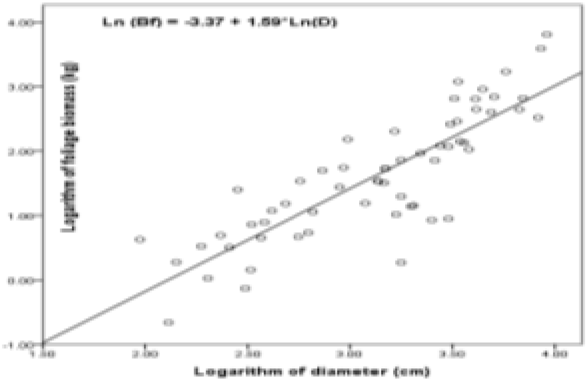
Model (1) and (2) include four equations of biomass for different tree components, and AGB and variables DBH, WD and H. Results show that the relationships between DBH and biomass of different tree components and AGB are very close ($R^2 = 0.72 \div 0.93$; and $R^2 = 0.67 \div 0.92$); T-test and F-test results indicate that the equations are statistically valid; CF and AIC values of the equations for AGB estimation are smallest, which indicates that Equation (1.8) and Equation (2.8) are the most optimal among equations following Model (1) and Model (2). The equation following Model (3) shows high coefficient of determination and low value of AIC; however, there are no significant difference in terms of AIC values compared with those of Equation (1.8) and Equation (2.8).

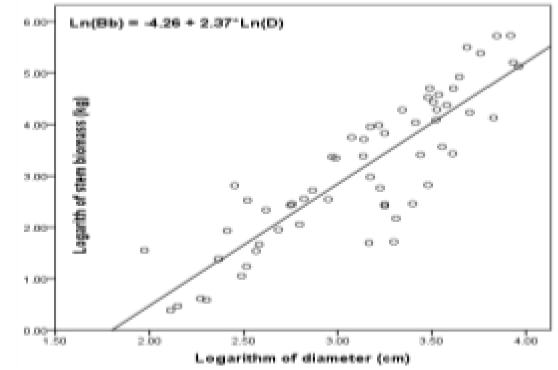
Table 18 Outputs of linear regression analysis for biomass estimation for decidious forest.

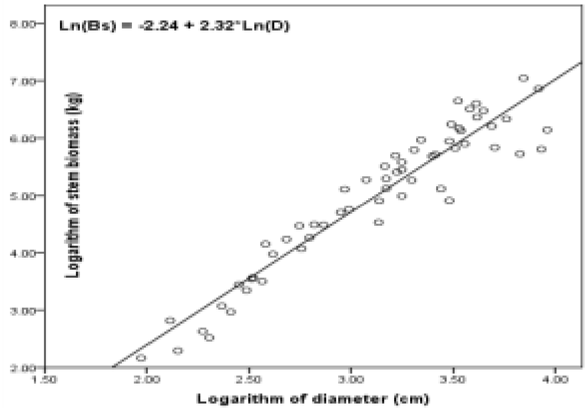
Model and predicted variables	Equation number	n	Interval of variables			γ	BF*	a	R^2	Sig.	CF	AIC
			DBH	H	ρ							
Model (1)												
Foliage biomass (Bf)	(1.5)	60	7.19 ÷ 52.50	NA	NA	-3.37	0.137	1.59	0.72	0.000	1.14	-77.53
Branch biomass (Bb)	(1.6)					-4.26	0.245	2.37	0.76	0.000	1.27	-42.70
Bole biomass (Bs)	(1.7)					- 2.23	0.074	2.32	0.91	0.000	1.08	-114.13
AGB	(1.8)					-1.99	0.056	2.31	0.93	0.000	1.06	-130.50
Model (2)												
Foliage biomass (Bf)	(2.5)	60	7.19 ÷ 52.50	5.4 ÷ 24		1.88	0.156	0.60	0.67	0.000	1.166	-69.87
Branch biomass (Bb)	(2.6)					3.53	0.296	0.88	0.71	0.000	1.338	-31.46
Bole biomass (Bs)	(2.7)					5.39	0.069	0.90	0.91	0.000	1.070	-118.65
AGB	(2.8)					5.560	0.060	0.89	0.92	0.000	1.061	-126.92
Model (3)												
AGB	(3.2)	60	7.19 ÷ 52.50	5.4 ÷ 24	0.64 ÷ 1.01	5.75	0.058	0.88	0.93	0.000	1.059	-128.84

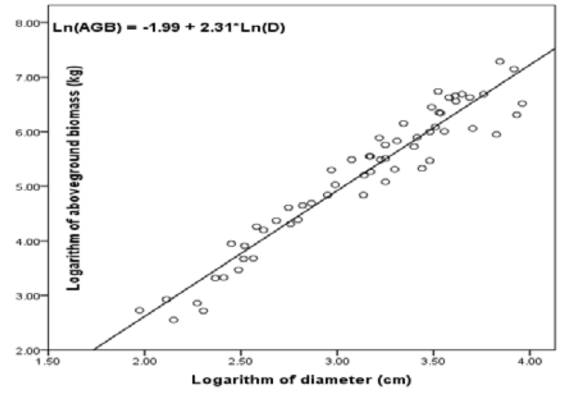
* Baskerville Factor

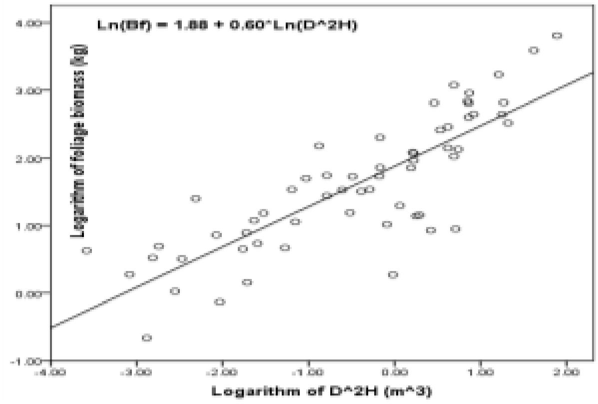
Equation (1.8) with the highest coefficient of determination and lowest AIC value may be more optimal than Equation (2.8) or Equation (3.2). Furthermore, Equation (1.8) is closest to a normal distribution (Figure 11). Nevertheless, the differences of CF and AIC values among equations (1.8), (2.8), and (3.2) are not significant, thus all three equations were employed for calculating average deviation generated from comparing observed and predicted biomass data.

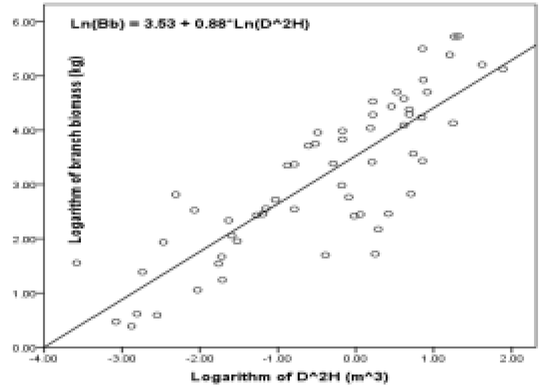


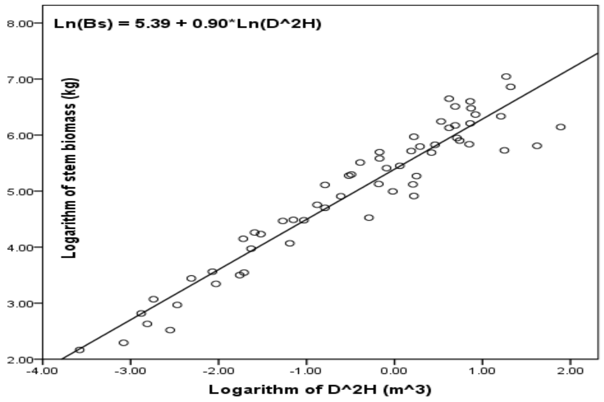


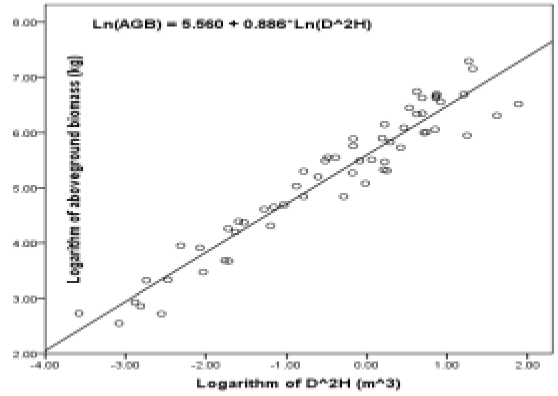












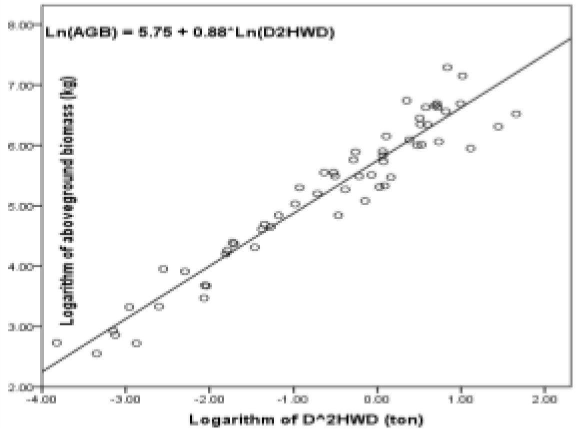


Figure 11 Linear regressions between AGB and biomass of tree components (foliage, branch, and bole) and DBH, H and WD of deciduous forest

Non-linear regression equations

Following the same steps in the development of non-linear allometric equations for EB forests, three equations were developed:

Equation following Model (5):

$Ln(AGB) = 5.687 - 6.89*Ln(DBH) + 3.53*(Ln(DBH))^2 – 0.44*(Ln(DBH)^3 - 0.039*Ln(WD)$ or
$AGB=295.01*exp(-6.89*Ln(DBH)+3.53*(Ln(DBH))^2 – 0.44*(Ln(DBH)^3 - 0.039*Ln(WD))$
Equation (5.2)

Equation following Model (6):

$Ln(AGB) = 4.491-4.97*Ln(DBH)+2.74*(Ln(DBH))^2 – 0.334(Ln(DBH))^3 + Ln(WD)$ or
$AGB = WD*exp(4.491-4.97*Ln(DBH)+2.74*(Ln(DBH))^2 – 0.334(Ln(DBH)^3)$
Equation (6.2)

Equation following Model (7):

$Ln(AGB) = -1.645 + 2.27*Ln(D) + Ln(WD)$ or
$AGB = WD*exp(-1.645 + 2.27*Ln(DBH))$ Equation (7.2)

The statistical analysis of four different models are presented in Table 19. Equation (4.2) is not valid statiscally, because one of parameters of the equation is not significant (sig. > 0.05). Coefficient of determination, CF and AIC value of Equation (6.2) are 0.93, 1.05, and -128.53, respectively and the same values for Equation (7.2) are 0.926, 1.058, and -128.05, respectively; the CF and AIC values for these two equations are similar. Equation (5.2) shows the highest coefficient of determination (R^2 = 0.94), and the smallest CF and AIC values (CF =1.05; AIC = -296.36) compared with Equation (6.2) and Equation (7.2). Based on these analyses, Equation (5.2) is the most optimal non-linear equation.

Table 19 Outputs of non-linear regression analysis for biomass estimation for decidious forests

Model	Equation number	n	Interval of variable			γ	BF[*]	a	b	C	d	R^2	Sig.	CF	AIC
			DBH	H	WD										
Model (4)															
	(4.2)	60	7.19 ÷ 52.50	5.4 ÷ 24	0.64 ÷ 1.01	2.07	NA	2.10	0.32[2*]	0.54[2*]	NA	0.92	0.000	1.55	-126.61
Model (5)															
	(5.2)	60	7.19 ÷ 52.50	5.4 ÷ 24	0.64 ÷ 1.01	5.64	0.047	-6.89	3.53	-0.44	-0.039	0.94	0.000	1.05	-296.36
Model (6)															
	(6.2)	60	7.19 ÷ 52.50	5.4 ÷ 24	0.64 ÷ 1.01	4.44	0.051	-4.97	2.74	-0.334	NA	0.93	0.000	1.05	-128.53
Model (7)															
	(7.2)	60	7.19 ÷ 52.50	5.4 ÷ 24	0.64 ÷ 1.01	-1.70	0.055	2.27	0	0	1	0.926	0.000	1.058	-128.05

[*] Baskerville Factor

[2*] Sig of T test > 0.05

Validation testing of the optimal equations

Through comparison of Equation (5.2) with the three optimal linear equations using average deviation of difference between observed biomass and predicted data from each equation, the most optimal equation was selected. Procedures and validation criteria were similar to those of EB forests.

Results showed that average deviations between true biomass of given seven sample trees and predicted values of each selected equation range from 21.17% to 26.97% (Table 20). Results indicate that Equation (1.8) has the highest average deviation with the second lowest AIC value. Equation (3.2) following Model (3) represents smallest average deviation between observed biomass data and predicted data (21.17%); the residuals between predicted values are also smallest (Annex 13).

Factoring in resource requirements in field measurement, Equation (1.8) is recommended as a practical option. Further validation of the equation using greater numbers of biomass samples, is suggested to help to ensure expanding applications in the whole region.

Table 20 Validation of equations for biomass estimation of deciduous forests

Equation	Bm (kg)	Bp (kg)	Average deviation (%)
Equation (1.8)	276.36	222.62	26.97
Equation (2.8)	276.36	224.03	23.38
Equation (3.2)	276.36	219.60	21.17
Equation (5.2)	276.36	182.825	24.98

4.3.3 Modeling of ABG for the main tree families and species

Not enough trees have been sampled in the main tree families and species to develop robust models.

4.3.4 Comparison with generic models

The allometric equation developed by Basuki (2009) for AGB estimation of deciduous forests in Indonesia ($AGB = 0.291*DBH^{2.178}$) was used to compare Equation (1.8) in terms of average deviation generated from observed and predicted data. Biomass data used for developing the most optimal equation was considered as true biomass data; while DBH of felled sample trees was used for estimating predicted biomass values of each equation; average deviation computed from true biomass values and predicted biomass data was used for comparing differences between different equations. Results indicate that the equation developed by Basuki shows high average deviation, approximately 55.71%; while the selected Equation (1.8) represents a lower average deviation at approximately 41.65%. The difference of average deviation indicates that Equation (1.8) increases accuracy in estimating AGB of deciduous forests in the Central Highlands (Figure 12).

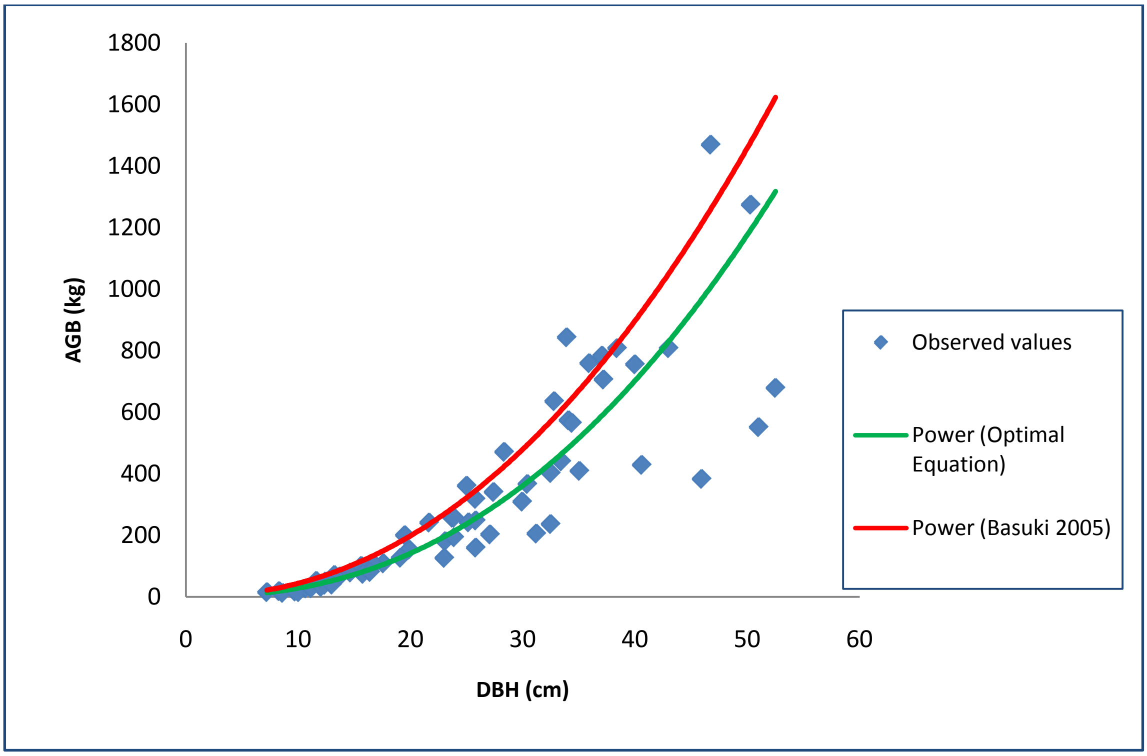


Figure 12 Comparison of Equation (1.8) (as optimal equation) with the equation of Basuki (2009)

4.4 Result 4: BEF (totalAGB/ABGstem)

The result for the 68 sampled trees in deciduous forest is a BEF average value of 1.26 ± 0.18. The minimal value is 1.04 and the maximal is 1.81.

5 RESULTS FOR BAMBOO (BAMBUSA PROCERA)

5.1 Result 1: Forest and trees characteristics

5.1.1 Forest characteristics: species composition and forest structure

Species composition

The average density of the surveyed plot of bamboo forests was 3,076 trees/ha, among which bamboos in the young age class account for 16%, medium aged class 17% and old aged class represent 66% of the total number. Observed distribution of N-DBH in different age classes varies (Table 21).

Table 21 Observed distribution of N-DBH in bamboo forests

DBH class (cm)	**Number of bamboo (tree/ha)**			
	young aged (N)	medium aged (N_M)	old aged (N_O)	Total (N)
2-3	12	12	28	52
3-4	96	102	180	378
4-5	110	188	284	582
5-6	74	128	522	724
6-7	124	70	676	870
7-8	76	28	316	420
8-9	2	6	38	46
9-10	0	0	4	4
Total	494	534	2,048	3,076

Forest structure

In the young-aged class, there is no clear rule for N-DBH distribution, with numerous trees distributed in DBH class 4-5 cm and 6-7 cm, and a declining tendency in DBH class 2-3 cm and 8-9 cm. In the medium-aged class, the observed N-DBH distribution reveals a clearer rule. The distribution is skewed to the left with trees concentrating in DBH class 4-5 cm, and N decreasing with increase in DBH size. In the old-aged class, observed distribution is skewed to the right, with the greatest N value in DBH class 6-7 cm (Figure 13).

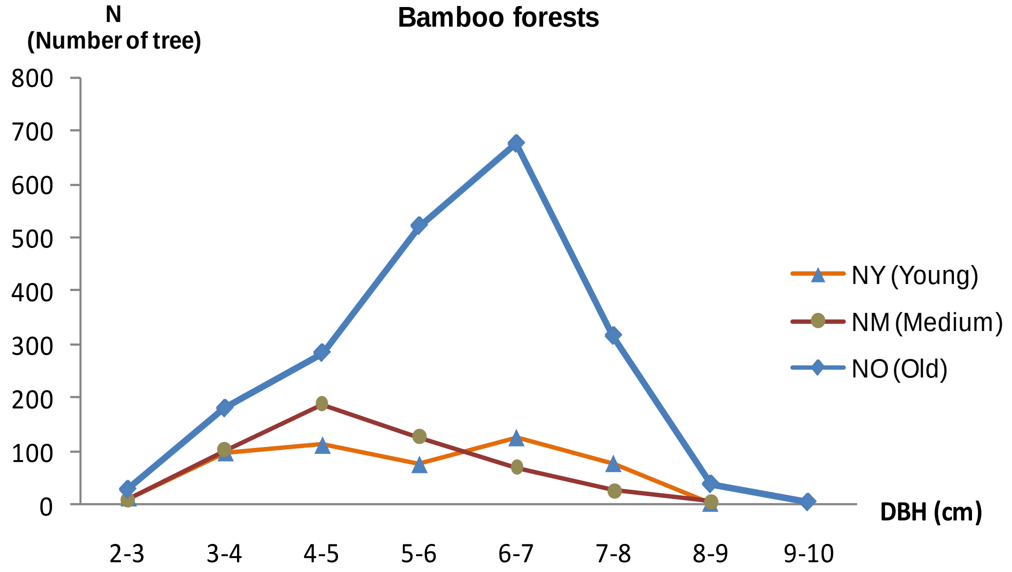


Figure 13 Observed distribution of N-DBH by aged stage of bamboo forest

Biomass of sample trees

Out of 138 sample bamboos for fresh biomass measurement, 75 sample bamboos were selected for dry mass analysis. The total number of samples was 320. 75 samples were taken for each component of stem, branch and foliage. The sample bamboos have DBH of 2.43-9.08 cm and H of 4.3-23.6 m.

The analysis results showed that the mean ratio of dry/fresh mass of stem for the young-aged class is 0.462 ± 0.024 (value range 0.437–0.468); branch is 0.390 ± 0.053 (value range 0.336-0.444); and foliage is 0.387 ±0.036 (value range 0.352-0.423). For the medium-aged class, the ratio of dry/fresh mass for stem is 0.513 ± 0.036 (value range 0.477-0.550); branch is 0.445 ± 0.024 (value range 0.421-0.469); and foliage is 0.373 ± 0.033 (value range 0.340-0.406). In the old-aged class, ratio for stem is 0.540 ± 0.018 (value range 0.522-0.550; branch is 0.487 ± 0.040 (value range 0.447-0.527), and for foliage is 0.425 ± 0.024 (value range 0.401-0.450) (Table 22 and Annex 6).

Table 22 Ratio of dry to fresh mass by age class & DBH class

Age class	**DBH class (cm)**	**n**	**Dry-fresh mass ratio (%)**		
			stem	branch	foliage
Young	2-3	1	0.481	0.481	0.403
	3-4	2	0.439	0.380	0.375
	4-5	3	0.473	0.353	0.405
	5-6	2	0.451	0.335	0.391
	6-7	2	0.424	0.390	0.313
	7-8	2	0.468	0.348	0.403
	8-9	2	0.495	0.443	0.421

	Mean		0.462	0.390	0.387
	SE		0.007	0.014	0.010
Medium	2-3	1	0.513	0.442	0.336
	3-4	4	0.492	0.433	0.387
	4-5	6	0.530	0.413	0.373
	5-6	2	0.555	0.464	0.390
	6-7	1	0.445	0.428	0.421
	7-8	5	0.542	0.485	0.378
	8-9	1	0.515	0.452	0.325
	Mean		0.513	0.445	0.373
	SE		0.008	0.005	0.007
Old	2-3	3	0.537	0.521	0.443
	3-4	8	0.551	0.468	0.407
	4-5	3	0.527	0.550	0.388
	5-6	13	0.514	0.451	0.428
	6-7	4	0.530	0.439	0.431
	7-8	3	0.560	0.504	0.463
	8-9	7	0.562	0.473	0.417
	Mean		0.540	0.487	0.425
	SE		0.003	0.006	0.004

Stem biomass occupies the largest share among the three components, with mean value of 76.2 ± 0.8% (value range 60.7-87.1%), followed by branch, with mean value of 16.4 ± 0.5% (value range 9.8-27.7%) and foliage. The share of foliage tends to decrease with increase in DBH. The average value for foliage biomass is 7.4 ± 0.4% (value range 3.2-18.2%) (Table 23).

Table 23 Average biomass structure by DBH class

Diameter class (cm)	**n**	**Share of biomass among components (%)**		
		Stem	Branch	Foliage
2-3	15	66.1	15.7	18.2
3-4	24	73.2	13.4	13.4
4-5	18	60.7	27.7	11.6
5-6	23	64.6	23.6	11.7
6-7	18	83.3	11.4	5.4

7-8	23	77.7	16.2	6.0
8-9	17	87.1	9.8	3.2
Mean (%)		76.2	16.4	7.4
SE		0.8	0.5	0.4

5.1.2 Relation between H and diameter

The relation between tree height and DBH has not been studied in this report.

5.2 Result 2: Modeling of the stem volume

The stem volume of bamboo trees has not been measured.

5.3 Result 3: Modeling of Aboveground biomass

5.3.1 Modeling per tree compartments

The study focused only on total aboveground biomass.

5.3.2 Modeling of total aboveground biomass

Linear regression equations

The development of linear allometric equations to estimate AGB of individual bamboo trees in bamboo forests was implemented for the different age classes. Results of graphic exploration indicate that the most normal distribution can be seen in the power model for the relationship between AGB and variables such as DBH and H. As discussed above, the linear model in the form of Ln (B) = γ + a*Ln(X) (where: B is biomass, γ, and a are parameters, and X known as variable of DBH or DBH^2H), was also used to develop equations for bamboo. Non-linear equations based on Equation (2), were not established for bamboo due to lack of WD data. Statistical analysis of equations between AGB/biomass of tree components and variable DBH are shown in Table 24. Equations for AGB following Model (1) are as follows:

$$\mathrm{Ln(AGB)} = -1.602 + 1.95 \cdot \mathrm{Ln(DBH)} \text{ or } \mathrm{AGB} = 0.201 \cdot \mathrm{DBH}^{1.95} \qquad \text{Equation (1.12)}$$

$$\mathrm{Ln(AGB)} = -1.868 + 2.31 \cdot \mathrm{Ln(DBH)} \text{ or } \mathrm{AGB} = 0.154 \cdot \mathrm{DBH}^{2.31} \qquad \text{Equation (1.16)}$$

$$\mathrm{Ln(AGB)} = -1.828 + 2.27 \cdot \mathrm{Ln(DBH)} \text{ or } \mathrm{AGB} = 0.160 \cdot \mathrm{DBH}^{2.27} \qquad \text{Equation (1.20)}$$

$$\mathrm{Ln(AGB)} = -1.703 + 2.16 \cdot \mathrm{Ln(DBH)} \text{ or } \mathrm{AGB} = 0.182 \cdot \mathrm{DBH}^{2.16} \qquad \text{Equation (1.24)}$$

Equations for stem biomass with DBH in respective age classes as variable, have the highest coefficients of determination, and lowest CF and AIC values while, equations between branch and foliage biomass and DBH have very low coefficients of determination ($R^2 = 0.081 \div 0.237$ for foliage; $R^2 = 0.20 \div 0.655$ for branch) and relatively high CF values. Coefficients of determination indicate that there are close relationships between dependent and independent variables (Table 24). The relationship between stem biomass and DBH of all age classes indicate higher coefficient, and lower CF and AIC values than those of the relationship between AGB and DBH; meanwhile equations between biomass of foliage/branch and DBH indicate very low coefficients of determination and high CF and AIC values. Although equations developed for stem biomass with variable DBH are statistically the optimal, these equations should not be associated with other relationships that have low coefficients of determination to estimate AGB. Furthermore, AIC values of equations between AGB and DBH for respective age classes are much higher than that of the equations for biomass/AGB and DBH of all age classes combined (AIC = -256.19). In addition, observed data of these equations between biomass/AGB and DBH are also closest to a normal distribution (Figure 14). Equation (1.24) is considered the most optimal equation for AGB of bamboo trees.

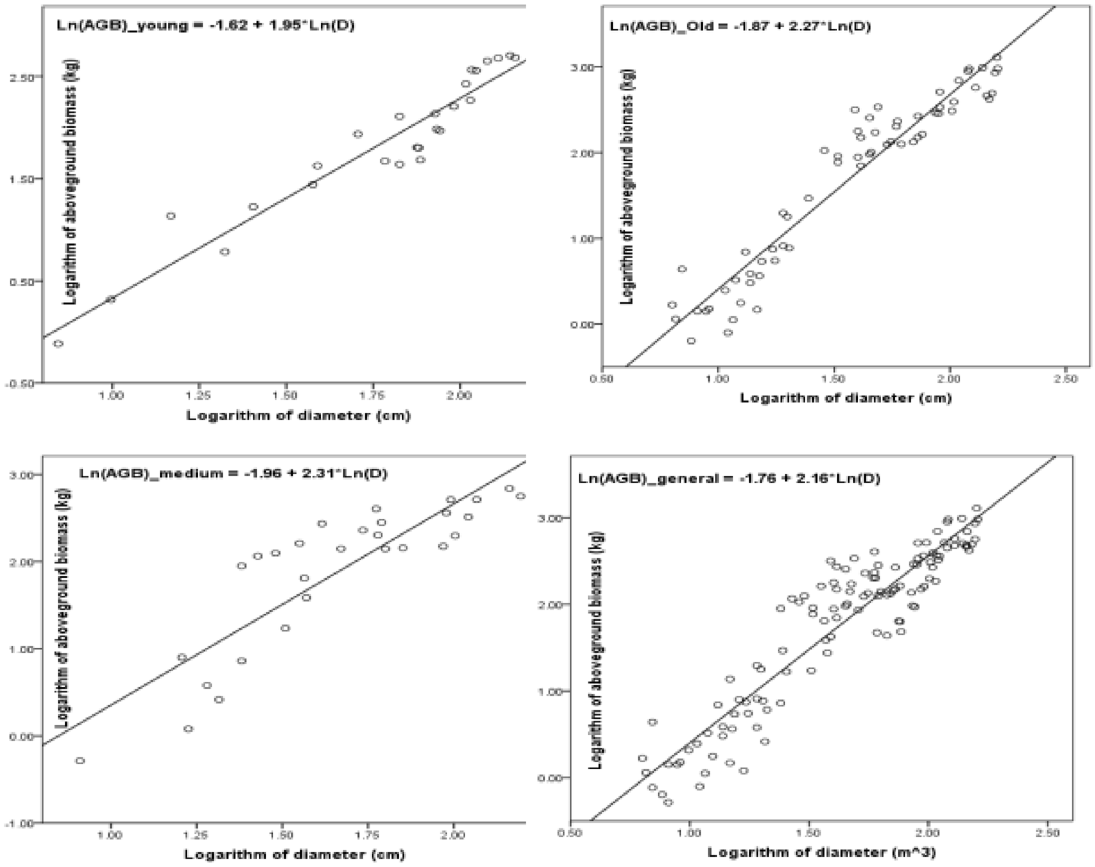


Figure 14 Linear regressions between AGB and DBH of bamboo

Table 24 Outputs of linear regression analysis of Model (1) for biomass estimation for bamboo

	Predicted variable	Equation number	n	Range of variables		γ	CE*	a	R^2	Sig.	CF	AIC
				DBH	H							
Young-aged class	Foliage biomass (Bf)	(1.9)	26	2.32 ÷ 8.66	6.80 ÷ 23.60	-2.42	0.318	0.65*	0.081	0.158	1.357	-9.79
	Branch biomass (Bb)	(1.10)				-1.97	0.163	0.22*	0.20	0.49	1.169	-27.26
	Stem biomass (Bs)	(1.11)				-2.15	0.022	2.18	0.935	0.000	1.021	-79.31
	AGB	(1.12)				-1.623	0.021	1.95	0.92	0.000	1.021	-79.46
Medium-aged class	Foliage biomass (Bf)	(1.13)	29	2.48 ÷ 8.98	6.30 ÷ 23.70	-2.99	0.457	1.40	0.187	0.019	1.55	-0.68
	Branch biomass (Bb)	(1.14)				-3.02	0.41	1.85	0.308	0.002	1.49	-3.52
	Stem biomass (Bs)	(1.15)				-2.58	0.047	2.47	0.874	0.000	1.047	-66.42
	AGB	(1.16)				-1.96	0.092	2.31	0.756	0.000	1.093	-47.082
Old-aged class	Foliage biomass (Bf)	(1.17)	64	2.23 ÷ 9.07	4.30 ÷ 22.4	-2.50	0.33	1.06	0.237	0.000	1.38	-24.28
	Branch biomass (Bb)	(1.18)				-3.99	0.294	2.46	0.655	0.000	1.33	-31.90
	Stem biomass (Bs)	(1.19)				-2.41	0.031	2.38	0.94	0.000	1.031	-175.84
	AGB	(1.20)				-1.87	0.042	2.27	0.92	0.000	1.042	-155.84
Age classes combined	Foliage biomass (Bf)	(1.21)	119	2.23 ÷ 9.07	4.30 ÷ 23.70	-2.39	0.387	0.92	0.146	0.000	1.46	-28.53
	Branch biomass (Bb)	(1.22)				-3.01	0.62	1.59	0.242	0.000	1.85	28.17
	Stem biomass (Bs)	(1.23)				-2.37	0.033	2.34	0.93	0.000	1.033	-320.90
	AGB	(1.24)				-1.76	0.057	2.16	0.86	0.000	1.058	-256.19

* Sig of t-test > 0.05

Statistical analysis of equations following Model (2) for AGB/biomass of tree components and variables DBH and H are shown in Table 25. Distribution of observed biomass data for different age classes and all age classes combined is presented in Figure 15. Equations between foliage/branch biomass and variables DBH and H show low coefficients of determination ($R^2 = 0.10 \div 0.31$; $R^2 = 0.037 \div 0.65$) and some of the equations are not valid statistically (Sig of t-test > 0.05). The equations between stem biomass and the combination of variables in respective age classes and all age classes combined presents very close correlations between dependent and independent variables ($R^2 = 0.92 \div 0.96$);, CF and AIC values of the relationships are always lower than those of other equations following Model (2). The equations following Model (2) for AGB for respective age classes and all classes combined are as follows:

$$\mathrm{Ln(AGB)} = 3.934 + 0.74*\mathrm{Ln(DBH)} \quad \text{or} \quad \mathrm{AGB} = 51.11*\mathrm{DBH}^{0.74} \quad \text{Equation (2.12)}$$

$$\mathrm{Ln(AGB)} = 4.749 + 0.84*\mathrm{Ln(DBH^2*H)} \quad \text{or} \quad \mathrm{AGB} = 155.46*(\mathrm{DBH^2*H})^{0.84} \quad \text{Equation (2.16)}$$

$$\mathrm{Ln(AGB)} = 4.68 + 0.82*\mathrm{Ln(DBH^2*H)} \quad \text{or} \quad \mathrm{AGB} = 107.98*(\mathrm{DBH^2*H})^{0.88} \quad \text{Equation (2.20)}$$

$$\mathrm{Ln(AGB)} = 4.39 + 0.76*\mathrm{Ln(DBH^2*H)} \quad \text{or} \quad \mathrm{AGB} = 80.56*(\mathrm{DBH^2*H})^{0.76} \quad \text{Equation (2.24)}$$

Statistical information indicates that equations for stem biomass with variables DBH and H are preferrable (Table 25). However, to estimate total AGB, association of separate equations for foliage, branch and stem biomass would become necessary; in addition, some of the equations for foliage and branch biomass show very low coefficients of determination or are not statically valid. In the observed biomass data, dispersed distribution can be seen in the equations for AGB with combination of variables for young-aged and medium-aged classes; meanwhile, for remaining equations (ie for old-aged and all ages combined), observed biomass data are quite close to a normal distribution, especially the equation for AGB estimation with variables DBH, and H of combined age classes (Figure 15).

In conclusion, Equation (2.24) is recommended as the optimal equation following Model (2) for AGB estimation, for its close correlation and low AIC value. This equation is also validated to determine average deviation between measured biomass and predicted biomass values for the comparasion with equation (1.24).

Table 25 Outputs of linear regression analysis of Model (2) for biomass estimation for bamboo

	Predicted variable	Equation number	n	Range of Variable		γ	CE*	a	R^2	Sig.	CF	AIC
				DBH	H							
Young-aged class	Foliage biomass (Bf)	(2.9)	26	2.32 ÷ 8.66	6.80 ÷ 23.60	-0.50*	NA	0.27*	0.10	0.115	NA	NA
	Branch biomass (Bb)	(2.10)				-1.25	NA	0.11*	0.037	0.346	NA	NA
	Bole biomass (Bs)	(2.11)				4.04	0.013	0.82	0.96	0.000	1.012	-93.05
	AGB	(2.12)				3.92	0.014	0.74	0.95	0.000	1.015	-87.60
Medium-aged class	Foliage biomass (Bf)	(2.13)	29	2.48 ÷ 8.98	6.30 ÷ 23.70	1195*	NA	0.56*	0.243	0.007	NA	NA
	Branch biomass (Bb)	(2.14)				2.30	0.403	0.67	0.327	0.001	1.47	-4.34
	Bole biomass (Bs)	(2.15)				4.49	0.027	0.89	0.926	0.000	1.027	-82.12
	AGB	(2.16)				4.68	0.069	0.84	0.82	0.000	1.068	-55.48
Old-aged class	Foliage biomass (Bf)	(2.17)	64	2.23 ÷ 9.07	4.30 ÷ 22.4	0.73	0.30	0.44	0.31	0.000	1.34	-30.67
	Branch biomass (Bb)	(2.18)				3.06	0.295	0.39	0.65	0.000	1.33	-31.83
	Bole biomass (Bs)	(2.19)				4.40	0.039	0.86	0.93	0.000	1.039	-161.20
	AGB	(2.20)				4.64	0.042	0.82	0.92	0.000	1.042	-156.38
Age classes combined	Foliage biomass (Bf)	(2.21)	119	2.23 ÷ 9.07	4.30 ÷ 23.70	0.305*	NA	0.357	0.18	0.000	NA	NA
	Branch biomass (Bb)	(2.22)				1.35	0.65	0.52	0.21	0.000	1.90	33.45
	Bole biomass (Bs)	(2.23)				4.24	0.035	0.83	0.92	0.000	1.036	-312.59
	AGB	(2.24)				4.33	0.059	0.76	0.86	0.000	1.061	-250.63

* Sig of T test > 0.05

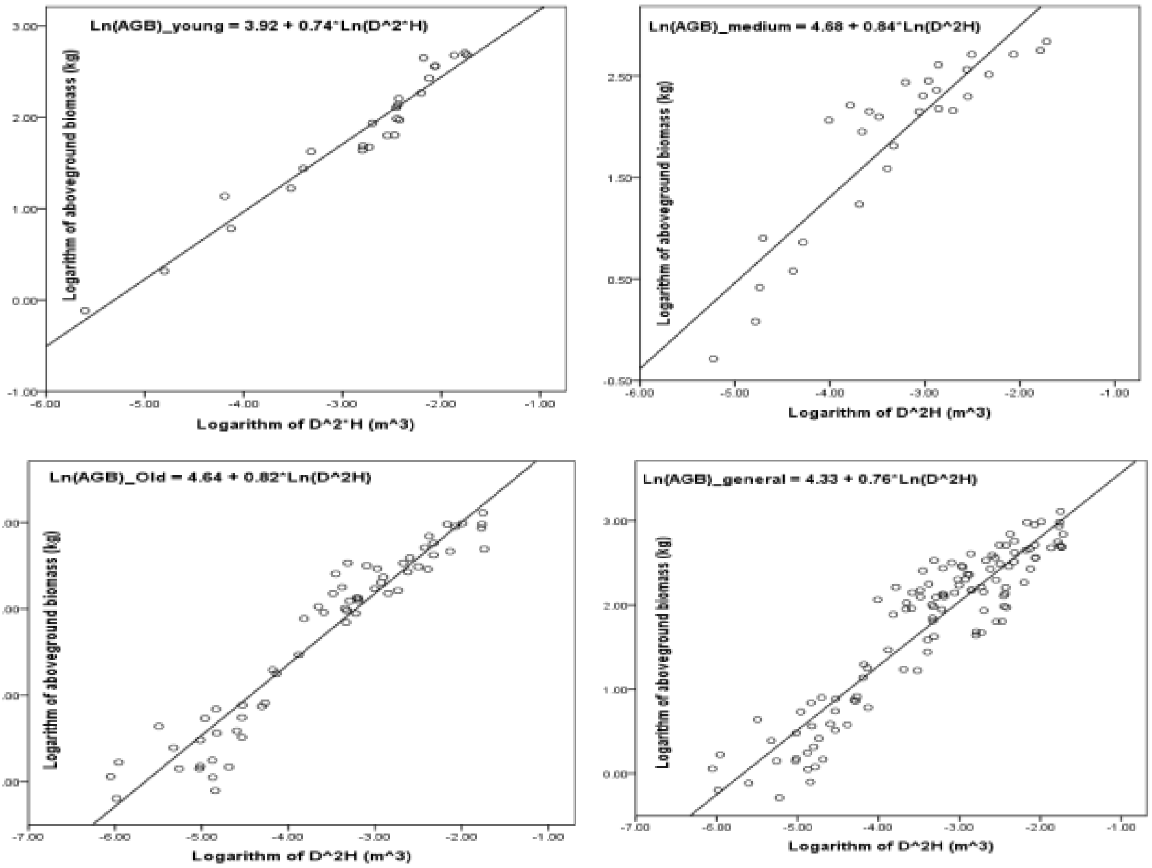


Figure 15 Linear regressions between AGB and the combination of DBH and H for bamboo

Validation testing of the optimal equations

Average deviation between measured and predicted biomass values of the optimal selected allometric equations was calculated by using DBH and biomass data of 20 sample trees that were randomly chosen from different age classes (Table 26).

Table 26 Validation of equations for biomass estimation of deciduous forest

#	Allometric equation	Bm (kg)	Bp (kg)	Average deviation (%)
1	$AGB = 0.182*DBH^{2.16}$	8.99	9.31	23.78
2	$AGB = 80.56*(DBH^{2}*H)^{0.76}$	8.99	9.07	31.10

There are significant differences in average deviation between measured and predicted biomass values generated from the optimal selected equation following Model (1) and Model (2) for bamboo. Equation (1.24) shows a lower average deviation compared with equation (2.24) (23.78% and 31.10%, respectively). Validation of the optimal selected allometric equations is conducted using CF and AIC values. Quantile plots of measured data and predicted values of Equation (1.24) and Equation (2.24) show that residuals between observed data and predicted data generated from Equation (1.24) is smaller than that of Equation (2.24) (**Annex 14**). The equation $AGB = 0.131*DBH^{2.28}$ (Hairiah et al., 2001) was used to compare the optimal equation generated from the study. The predicted biomass from Equation (1.24) was 9.7% higher than that of the equation developed by Priyadarsini (adapted from Hairiah et al., 2001). On the other hand, average deviation of Equation (1.24) generated from predicted values and observed biomass data of 119 tree samples used to develop the equation was approximately 7% higher than that of the equation developed by Priyadarsini (32.81% compared with 25.01%). Thus, Equation (1.24) may result in lower accuracy compared with equation of Priyadarsini. It is recommended that more biomass data of bamboo should be tested for further improvement of Equation (1.24) to increase accuracy.

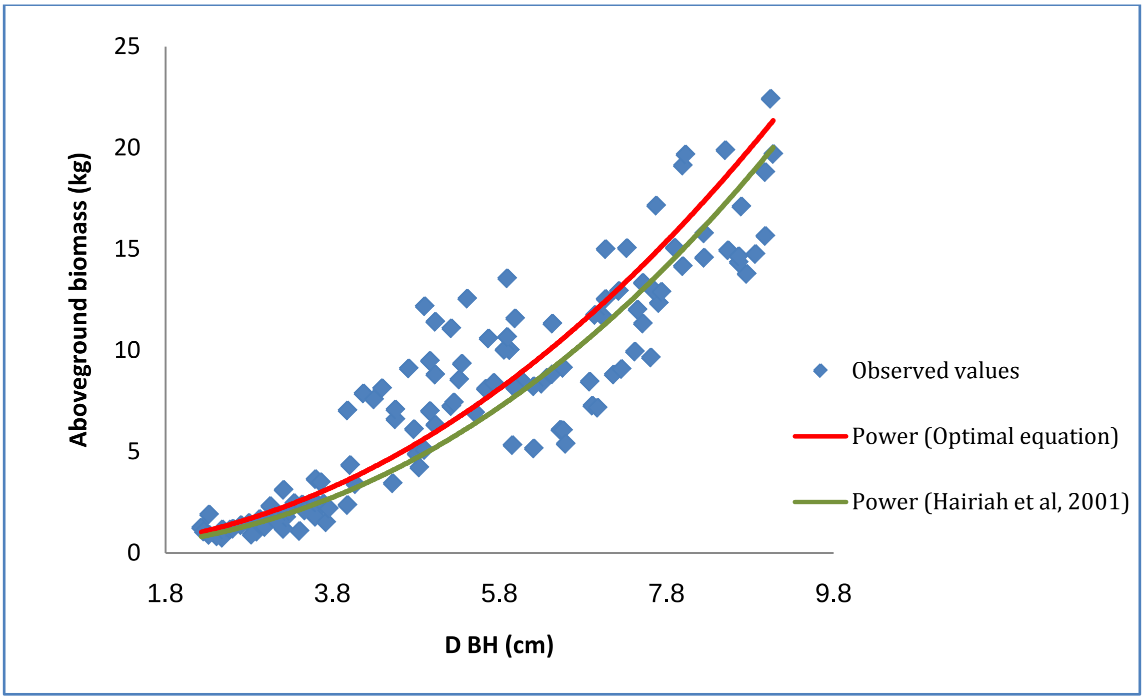


Figure 16 Comparison of Equation (1.24) as optimal equation and equation of Hairiah et al., (2001) between AGB, DBH, and H of bamboo

5.4 Result 4: BEF (totalAGB/ABGstem)

The result for the 75 bamboo trees sampled in is a BEF average value of 1.39 ± 0.30. The minimal value is 1.02 and the maximal is 2.59.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Biomass of bole, branch and foliage greatly varies depending on species and tree size. However, there is a general tendency that biomass of bole is the highest, followed by branch and foliage biomass.

For EB forests, biomass of bole accounts for 76.1±0.42% (value range 68.3-82.5%) of its total biomass; branch accounts for 21.6±0.41% (value range 14.9-28.7%) and foliage accounts for 0.38 ± 0.06% (value range 1.5-3.2%).

For deciduous forests, biomass of bole accouts for 81.3 ± 1.0% (value range 60.1-84.0%); branch accounts for 16.2 ± 0.9% (value range 10.0-31.5%); and foliage accounts for 2.4±0.2% (value range 1.2-7.8%).

For bamboo, stem biomass was estimated at 76.2±0.8% (value range 60.7-87.1%); branch accounts for 16.4±0.5% (value range 11.4-27.7%) and foliage accounts for 7.4±0.4% (value range 5.4-18.2%).

WD data was generated for 18 species from EB forests and 14 species from deciduous forests. The WD varies greatly from among species. For EB forests, the mean WD value is 0.722 ± 0.035 g/cm^3 (value range 0.683-0.760 g/cm^3). The maximum value of WD is 0.981g/cm^3 and the minimum value of WD is 0.393 g/cm^3. For deciduous forest, mean value of WD is 0.847±0.093 g/cm^3 (0.754-0.941 g/cm^3); the maximum value is 1.098 g/cm^3; and minimum value is 0.596 g/cm^3.

A number of allometric equations were developed for forest biomass estimation in the form of linear and non-linear regressions. A total of 50 equations were developed for biomass estimation based on variables of DBH, H and WD.

For EB forests, the optimal equations developed for estimating AGB are as follows:

$$AGB = 0.222*DBH^{2.387} \qquad \text{Equation (1.4)}$$

$$AGB = 0.098*\exp(2.08*Ln(DBH) + 0.71*Ln(H) + 1.12*Ln(WD)) \qquad \text{Equation (4.1).}$$

On comparison with published studies, Equation (4.1) was found to have higher accuracy in biomass estimation compared with the equation suggested by Chavel (2005); while Equation (1.4) may result in significant errors in biomass estimation compared with the equation developed by Brown (2001).

The optimal equation for AGB estimation of deciduous forests is as follows:

$$AGB = 0.14*DBH^{2.31} \qquad \text{Equation (1.8)}$$

On comparison with the equation of Basuki (2009), Equation (1.8) was considered preferable for biomass estimation of deciduous forests in the Central Highlands of Viet Nam.

The optimal equation for AGB estimation of bamboo is as follows:

$$AGB = 0.182*DBH^{2.16} \qquad \text{Equation (1.24)}$$

However, average deviation indicates that the selected equation is less suitable than the equation developed by Priyadarsini for AGB estimation for bamboo forests in Central Highlands.

6.2 Recommendations

As there is a small sample trees for validation of developed equations for AGB estimation, it is recommended to use data of sample trees collected in other studied regions to cross – check and validation.

Biomass data from this study should be associated with data of the same forest types in different ecological regions within the country to develop general allometric equations that can be applied for AGB estimation of forests in other regions where equations are not available.

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