UN-REDD PROGRAMME

Part B-1: Tree allometric equations in Evergreen broadleaf forests in the South Central Coastal region, Viet Nam

UN-REDD PROGRAMME
Viet Nam

October 2012
Hanoi, Viet Nam

Tree allometric equation development for estimation of forest above-ground biomass in Viet Nam - Evergreen Broadleaf Forests in the South Central Coastal region

By

Bao Huy, Vo Hung, Nguyen Thi Thanh Huong, Cao Thi Ly, Nguyen Duc Dinh
Department of Forest Resource and Environment Management (FREM), Tay Nguyen University

Edited by: Akiko Inoguchi, Gael Sola, Matieu Henry and Luca Birigazzi, FAO

Recommended citation: Huy, B., Hung, V., Huong, N.T.T., Ly, C.T., Dinh, N.D. (2012) Tree allometric equations in Evergreen Broadleaf Forests in the South Central Coastal region, Viet Nam, in (Eds) Inoguchi, A., Henry, M. Birigazzi, L. Sola, G. Tree allometric equation development for estimation of forest above-ground biomass in Viet Nam, UN-REDD Programme, Hanoi, Viet Nam.

ACKNOWLEDGEMENT

To conduct this research, the study group from Department of Forest Resources and Environment Management (FREM), Tay Nguyen University received support and helpfrom organizations, agencies, individuals, in particular the below mentioned:

General Department of Forestry and UN-REDD Vietnam have coordinated to FREM study group to conduct research in the Vietnamese Central region and monitored the process as well.

Financial support of the FAO and their method advice during the time we performed this research.

QuangNam Provincial People's Committee, Department of Agriculture and Rural Development QuangNam, Sub-Department Forestry granted the permission of felling trees for the research.

Sub-department of forest protection of PhuocSon District and Phuoc Xuan Commune People's Committee took part in selecting the study site and co-monitoring the process of sampling trees.

Local people from Village Hoi of Phuoc Xuan Communeand people from Daklak participated in fieldwork such felling tree, collecting biomass and taking samples.

Forestry and Forest resources and environment management university students and master student from Tay Nguyen University enthusiastically joined into most of research process in the field and laboratory as well.

FREM researchers have most effective and quality participation during the research process.

This research not only required appropriate methods and organization for performing, but also needed support for legislation to fell forest trees, especially costs for heavy labor to carry out during inventory process such as felling trees, biomass weighing, sampling, sample analysis, and so forth. Therefore results obtained from this study is with the contribution of all stakeholders mentioned above, the research team would like to extend our gratitude to all the support and contributions.

Leader of research Team

Assoc. Prof. Dr. Bao Huy

Study team members

Name	Title	Institution	Reasonability
Bảo Huy	Assoc.Prof.Dr.	TayNguyen University	Leader team
Võ Hùng	Dr.	TayNguyen University	Member
Nguyễn Thị Thanh Hương	Dr.	TayNguyen University	Member
Cao Thị Lý	Dr.	TayNguyen University	Member
Nguyễn Đức Định	MSc.	TayNguyen University	Member
Nguyễn Công Tài Anh	Eng.	TayNguyen University	Member
Nguyễn Thế Hiển	Eng.	TayNguyen University	Member
Phạm Đoàn Phú Quốc	Eng	TayNguyen University	Member
Master and university students		TayNguyen University	Fieldwork, Laboratory work
Involved people		Village Hoi, Phuoc Xuan commune, Phuoc Son district, Quang Nam province, Daklak province	Fieldwork

EXECUTIVE SUMMARY

The main focus of this study is to develop biomass allometric equations for evergreen broadleaved forest in the Central region of Vietnam. Two sample plots with an area of 1ha each were designed to measure inventory factors. The number of trees sampled in these plots was 110 from 2 plots. Trees selection was based on dominant species, and proportion of number of trees by diameter class. Destructive sampling method was used to collect sample trees. Total biomass of individual tree was determined based on fresh and dry biomass of 5 components: stem, bark, branch, leave and stump. Additional wood density of each component was specified in the laboratory. Of which 110 sample trees 90 trees were used to develop allometric equations while 20 trees were employed as the independent data for the validation of the models. The results show there was somewhat relation between the above ground biomass (AGB) and four variables: diameter at breast height (DBH), tree height (H), wood density (WD), and crown area (CA). This was basis for developing estimates of AGB from one to more than one of these four variables.

The indicators used for model selection are R_2 adjusted, T-test for testing the significance of estimates of each parameter, Correction factor(CF), Mallow's Cp, Akaike Information Criterion(AIC) and Average deviation between estimated values and observed values (S%). The average deviation in the current study (S% = 13%-16%) exhibited lower than those of authors who conducted models for tropical moist forests as Brown (1997) offered a model with S% =43% -107%, Chave (2005) with S% =52% -94%,and Basuki et al.(2009) with S%=26% 30%. This indicates specific biomass estimates for each forest type in the ecological regions of Vietnam is necessary to improve reliability and accuracy. Besides the variables of DBH and H, WD is very important to enhance the accuracy of AGB estimation as it reflects biomass by species. Explanation variable of CA represented biomass variation of branch and leave even if the same DBH, H and WD but different species. CA helps to improve accuracy of the biomass models while the allometric equations for each species have not still been performed in complex conditions as tropical forest of Vietnam.

The AGB is closely related to plant family. However, with the limited number of trees felled in this study, designing AGB equations for each plant family was not possible. It is recommended that further studies look into such model development with adequate numbers of sample trees.

The selected equation for estimating stem volume:

$$log(\mathrm{V}) = -9.68839 + 0.956145 * \log(\mathrm{DBH}^2 * \mathrm{H})$$

(log: Logarit neper)

The selected models for AGB estimation with DBH only:

$$\mathrm{AGB_{tree}} = \exp(-2.24267 + 2.47464 * \ln(\mathrm{DBH}))$$

and the one with the best accuracy:

$$\log(\mathrm{AGBtree}) = -2.23222 + 0.744261 * \log(\mathrm{DBH}^2 * \mathrm{H}) + 1.13674 * \log(\mathrm{WD}) + 0.17046 * \log(\mathrm{DBH}^2 * \mathrm{CA})$$

The average BCEF = 0.658 t/m^3 witth standard deviation is 0.153; and BEF = 1.365 with standard deviation is 0.171

Using the best equations, estimation of timeber volume and total AGB per ha in the studied forest, the volume per ha: 400.6 – 534.7 m^3/ha and the total AGB per ha: 259.8 – 347.4 ton/ha.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

A	Age, year
AGB	Above ground biomass (kg/tree)
AGBf	Fresh Above ground biomass (kg/tree)
BA	Basal area (m^2/ha)
Bba	Biomass of bark (kg/tree)
Bbr	Biomass of branch (kg/tree)
BCEF	Biomass Conversion and Expansion Factor (t/m^3)
BEF	Biomass Expansion Factor
Bfba	Fresh biomass of bark (kg/tree)
Bfbr	Fresh biomass of branch (kg/tree)
Bfl	Fresh biomass of leaf (kg/tree)
Bfst	Fresh biomass of stem without bark (kg/tree)
Bfst+ba	Fresh biomass of stem with bark (kg/tree)
Bfstu	Fresh biomass of stump enlargement (kg/tree)
Bl	Biomass of leaf (kg/tree)
Boi	Bark thick at position of 1/5 length (mm)
Bst	Biomass of stem without bark (kg/tree)
Bstu	Biomass of stump enlargement (kg/tree)
C(AGB)	Carbon in ABG (kg/tree)
CA	Crown Area (m^2)
CD	Crown diameter (m)
CF	Carbon Fraction
COP	Conference of the Parties (to the United Nations Framework Convention on Climate Change: UNFCCC)
D1/2L	Diameter at middle position of tree (cm)
DBH, D, $D_{1.3}$	Diameter at Breast Height (usually at 1.3m from ground) (cm)
dfba	Fresh bark density (g/cm^3)
Doi	Diameter at positions of 1/5 tree length: root, 1/5L, 2/5L, 3/5L and 4/5L, sequent signing 00, 01, 02, 03, 04 and 05 (cm)
Doinonba	Diameter without bark corresponding with Doi (cm)
Dstump	Diameter at stump (cm)
FAO	Food and Agriculture Organization
FCCC	Framework Convention on Climate Change
FCPF	Forest Carbon Partnership Facility (World Bank)
GHG	Green House Gas
GSL/M	Growing stock level
H, L	Tree Height, Length (m)
Hstump	Stump height (m)
IPCC	Intergovernmental Panel on Climate Change
LatD10	Tree length to position of diameter at 10cm
Lunderbr	Commercial length (m)
M	Stand volume(m^3/ha)
N	Density (tree/ha)

REDD	Reducing Emissions from Deforestation and Forest Degradation
REDD+	Reducing Emissions from Deforestation and Forest Degradation plus biodiversity conservation
UNDP	Unite Nations Development Programme
UNEP	Unite Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UN-REDD	United Nation – Reducing Emissions from Deforestation and Forest Degradation
V	Tree volume (m^3/tree)
Vba	Bark volume (m^3/tree)
Vnonba	Tree volume without bark (m^3/tree)
WD	Wood density (g/cm^3)

1 OBJECTIVES

1.1 Research objectives

The objective of the survey and study was to develop allometric equations for evergreen broadleaf forests in the South Central Coastal region of Vietnam. There are currently no existing allometric equations for this forest type and eco-region.

1.2 Research contents

The research was carried out for the following;

- Tree components: stem, branch, leave, stump and bark
- Relevant variables: DBH, H, WD, CA, tree species, plant family
- Forest type: Evergreen Broadleaf
- Forest status: low disturbance (corresponding to rich status "IIIB" and "$IIIA_3$": primary and rich forests according to the Vietnamese forest status classification employed in the National Forest Inventory, Monitoring and Assessment Programme).

The following analysis was conducted:

- Analysis of species composition, structure, wood density and relationship among forest variables:
- Relationship between H and DBH; and estimate of tree volume (V) based on H and DBH.
- N/DBH; Basal area, V/DBH class
- Average of wood density (WD) of essential tree species
- AGB estimates:
    - Modeling based on DBH
    - Modeling based on two variables of DBH and H
    - Modeling based on DBH, H and WD
    - Modeling based on DBH, H and CA
    - Model based on DBH, H, WD and CA
    - Model based on standing tree volume (V)

2 MATERIALS AND METHODS

2.1 Study site

The specified forest type and eco-region for this study are the Broadleaf-Evergreen Forests of South Central Coastal Vietnam, specifically in Quang Nam province. The survey sites are located in Phuoc Xuan village, Phuoc Son district, Quang Nam province, including 2 sample plots (SPI and SPII)

Table 1: Geographic coordinates of the study sites

Coordinates	**SPI**	**SPII**
Latitude	$15^{0}28'13.3''$	$15^{o}28'16.1''$
Longitude	$107^{o}48'59.6''$	$107^{o}48'56.6''$
UTM		
Latitude	Y = 1712334	Y = 1712417
Longitude	X = 802234	X = 802146
VN2000		
Latitude	Y = 1710465	Y = 1711065
Longitude	X = 506946	X = 506859

Figure 1: Study site image (source: Google Earth)

2.2 Study site characteristic[1]

2.2.1 Soil and topology

The soil conditions of the surveyed sites is yellow brown soil developed on ancient alluvial (Fp) that distributes on lowland of Kham Duc town with pH = 6.0-6.3, soil depth layers >100 cm. The study site is also located in slopes and tops of mountains with slopes of10-40 degrees. The elevation above sea level is 574-624m.

2.2.2 Climate and hydrology

The mean annual precipitation is 3,150-3,500 mm, and minimum precipitation is 1,857mm, while maximum is 5,337mm. The average annual temperature is 21.8^{0}C; the hottest temperature is 39.4^{0}C, while the coldest is 16^{0}C. The location has two distinct seasons: The dry season from February to August and the rainy season from September to January. The common wind direction in the winter is northeastern monsoon. The average humidity is 90%, the mean evaporation is 800mm. Foggy usually from November to February.

Because of high precipitation, water resources, which flow into big rivers (e.g. Dak My 56km), are plentiful. Truong River flows into Gia River and Tra No River flows into Thu Bon River. Additional Dak Mek River, Dak Glon Spring, Dak Xa Oa Spring is the plentiful water resources flowing to the big rivers and running to delta regions then.

2.3 Sample plot designing and measuring

Two sample plots were conducted with an area of 1ha (100*100m), each divided into 100 sub-plots with an area of 10*10m.

For the plot with slope, the length of plot R' was computed as:

$$R' = R / \cos \alpha$$

where R': length on slope, R: length of plot in horizontal land (map),α: slope (degree)

Data collection and sampling within sample plot comprised of:

- Position of plot: Administrative position information such as commune, district, province; coordinates, forest owner.
- Stand information: forest status, dominant species, canopy, species of vegetation, and its percentage coverage.
- Topology: plot position, aspect, elevation above sea level
- Meteorology and climate, including: average rainfall per year, air temperature, humidity. Someaverageannualfactorswerecollectedatthenearesthydro-meteorological station.
- Soil characteristics including: Mother soil, soil type, soil texture, gravel, exposed stone, pH, and soil depth
- Standing tree: measurement of all trees having DBH ≥ 5 cm within the plot with variables such as Vietnamese species name, DBH, and tree form quality with three levels a: good, b: medium, c: bad.

[1] Source: Web site of Phuoc Son Distict: http://www.phuocson.gov.vn.

Data collected were transcribed in excel spread sheets. (Available as database for AE development Quang Nam TNU, sheet: O TC I and O TC II.)

Sample plot I (SP I)

Sample plot II (SP II)

Figure 2: Picture of sample plots

2.4 Selection of the sampling trees

The selection of the tree is the result of diameter measurement of all the trees within each plot. The sampled trees were selected based on dominance in the stand. 55 trees were sampled for each plot, of which 45 trees were employed for developing AEs and the remaining for validation (Table 2, Table 3).

Table 2: Sampled trees

DBH class (cm)	#of standing trees in the sample plot		# of felled trees for modeling		# of felled trees for validation		Total # of trees cut for modeling	Total #of trees cut for validation
	SP I	SP II	SP I	SP II	SP I	SP II		
5 –15	803	681	22	23	3	4	45	7
15 –25	229	231	8	8	2	1	16	3
25 –35	119	77	4	2	0	1	6	1
35 - 45	58	51	2	5	1	1	7	2
45 - 55	23	20	4	4	1	1	8	2
55 - 65	16	6	2	1	1	1	3	2
65 - 75	8	3	1	1	1	1	2	2
75 - 85	6	4	1	1	1	0	2	1
85 - 95	2	0	1	0	0	0	1	0
95 - 105	1	3	0	0	0	0	0	0
Total	1265	1076	45	45	10	10	90	20

Table 3: Number of the trees felled per main tree family

Id	Family name	Number of trees felled
1	Anacardiaceae	1
2	Annonaceae	6
3	Aquifoliaceae	1
4	Burseraceae	7
5	Calophyllaceae	1
6	Clusiaceae	4
7	Combretaceae	1
8	Dilleniaceae	4
9	Dipterocarpaceae	7
10	Ebenaceae	4
11	Elaeocarpaceea	3
12	Euphorbiaceae	4
13	Fagaceae	7
14	Lauraceae	3
15	Lecythidaceae	3
16	Magnoliaceae	3
17	Meliaceae	6
18	Myristicaceae	5
19	Myrtaceae	8
20	Rosaceae	1
21	Rubiaceae	2
22	Rutaceae	3
23	Sapindaceae	2
24	Sapotaceae	3
25	Sterculiaceae	11
26	Styraceae	1
27	Theaceae	4
28	Ulmaceae	4
29	Verbenaceae	1
	Total	**110**

Total of 29 tree families with 110 tree felled, number of trees felled per main family from 1 – 11 trees.

2.5 Measured variables of sample trees felled

The main approaches applied were destructive sampling according to DBH classes and dominant species to identify fresh and dry biomass (c.f. Destructive Measurement Guidelines, 2012). Based on analysis of sample trees, different algorithms were tested to define biomass models through forest variables which can be measured directly.

2.5.1 Destructive sampling

Within the 1ha sample plots, destructive sampling was applied, and stems segmented into diameter into equal parts with diameter range of 10cm intervals. The smallest and largest diameter classes sampled were at 5-15cm, and 85-95cmrespectively. Within each diameter class, the number of trees sampled was determined based on the ratio of trees within each diameter class, while for the larger diameter classes (i.e. DBH 45-95cm)at least three trees were sampled. The sampled trees were selected based on dominance in the stand. 55 trees were sampled for each plot, of which 45 trees were employed for developing AEs and the remaining for validation (Table 2).

Felling sample trees | Cutting stem into segments | Cutting branches | Collecting leaf

Figure 3: Images from sampling survey

Measured tree variables and biomass components of felled sample trees:

- Standing trees: DBH, H, crown diameter (CD) (measuring 2 trends of North-South and East-West), and species identification.
- Felled trees: Age (A), length (L), stem length under branches, commercial length, length at position of diameter at 10cm, stump height, diameter at middle of stem.
- Variables for computing tree volume with and without bark: The felled trees were divided into 5 equal parts of one fifth length and diameters with and without bark were specified in every part accordingly. (The diameter from the first to the fifth called D_{00}, D_{01}, D_{02}, D_{03}, D_{04} respectively.)

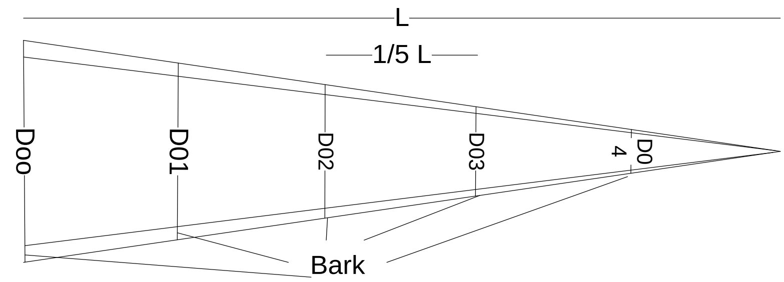


Figure 4: Division method of felled stem into 5 equal lengths for calculating volume

Weighing leaves

Weighing stem and bark

Weighing branches

Figure 5: Images of weighing fresh biomass of sample tree components

Weighing fresh biomass of tree components:

The fresh weight of the leaves, bark, branches and stem with bark were weighed in the field using electronic weighing scales of 300 kg capacity with accuracy 0.1kg.

To separate the bark from the stem, at position of one fifth length fresh bark samples were taken and weighed (m) with accuracy of 0.1mg. The bark volume (Vba)of the sample was identified as the volume of the water displaced when submerged in vitreous tube with accuracy of ml (cm^3).

Fresh bark weight (Bfba) was indirectly calculated based on fresh bark density (dfba); dfba is calculated as:

$$dba = m/Vba \qquad \text{Equation 3-1}$$

$$Bfba = dfba * Vba. 10^3 \qquad \text{Equation 3-2}$$

where, Vba is the bark volume of the tree determined from the volume with and without bark of five segments of the stem.

Fresh biomass of stem (Bfst) was determined as:

$$Bfst = Bfst + ba - Bfba \qquad \text{Equation 3-3}$$

Preparing samples of four tree components for biomass and wood density calculation:

The samples used to determine biomass of four above-ground tree components (i.e. stem, branches, leaves and bark) included110 felled trees (440samples).For stems and branches, each sample size was 500g, while leaves and bark, each sample size was 300g. An electronic balance with accuracy of 0.01g was used to weigh the samples.

For wood density (WD),samples were taken from the segmented stem parts into five equal lengths, for each sample tree. Total number of samples: 110 trees * 5 sample = 550 samples.

Branch samples

Leaf samples

Sample for WD determination

Bark samples

Stem sample

Set of each tree samples

Figure 6: Images of samples of tree components

2.6 Laboratory measurements

2.6.1 Analysis of dry biomass and wood density

All samples were analyzed in a laboratory to determine dry biomass and WD.

Dry biomass of tree components:

The samples were bifurcated into small pieces and dried at a temperature of 105^{o}C until constant weight was achieved (at least 48hours). Based on this, ratio of dry biomass/fresh biomass of the four tree components were determined.

Wood density (WD):

The fresh volume (v) of each sample was determined by the volume of the water displaced when submerged in vitreous tube with accuracy of ml (cm^{3}). Dry biomass (m) of each sample was defined as dry oven temperature of 105^{o}C until the weight of the sample was completely dry (saturation status) (at least 48 hours with samples cut into specimen). WD of each sample tree was obtained as the average of the five stem segments.

$$WD = m/v \qquad \text{Equation 3-4}$$

Wood volume determination

Preparation of samples for calculating dry biomass and analysis of carbon

Oven drying at 105^{0}C

Samples for drying and carbon analysis

Figure 7: Images of dry biomass and WD analysis

2.7 Other variables

2.7.1 Formulas employed for calculation of biomass

Ratio of species composition was calculated as important value (IV):

$$IV = (N + BA)/2 \quad \text{Equation 3-5}$$

where, N(%)is the ratio of the specific species in the whole stand; BA(%) is BA ratio of specific species compared with the whole stand. Dominant species is determined as the species with highest IV in the stand and total IV of these species is over 50%.

The tree volume with and without bark were calculated as Hohenadl (1923):

$$V = \frac{L.\pi.10^{-4}}{80}\{(Doo + D01)^2 + (Do1 + D02)^2 + (Do2 + D03)^2 + (Do3 + D04)^2 + (D04)^2\} \quad \text{Equation 3-6}$$

where, V (m^3) is volume with bark (V); (Vnonba) is volume without bark. Bark volume (Vba) = V – Vnonba (m^3); L(m) is tree length; Doi (cm) is diameter of 5 stem segments, with or without bark.

Crown area(m^2) is:

$$CA = \pi.CD^2/4 \quad \text{Equation 3-7}$$

where, CD is average crown diameter(m).

Dry biomass of each tree component = fresh weight x ratio dry and fresh

Above ground biomass of tree (kg) is:

$$AGB_{tree} = Bst + Bbr + Bl + Bba + Bstu \quad \text{Equation 3-8}$$

Biomass Conversion and Expansion Factor (BCEF) (t/m^3) (IPCC, 2003)

$$BCEF = AGB_{tree}/V \quad \text{Equation 3-9}$$

Biomass Expansion Factor (BEF) is (IPCC, 2003):

$$BEF = AGB/Bst \quad \text{Equation 3-10}$$

Variables such as density (N, tree/ha), basal area (BA, m^2/ha), stand volume (M, m^3/ha) were calculated as equations used in forest inventory.

A database of 110 sample trees with biomass of different components was created.[2]

Of 110 sample trees, 90 trees were used to develop the models, while 20 trees were employed for model validation. The independent data used for validation was derived from randomly selected tree selected on the basis of diameter class. Ten trees were cut for each plot.[3]

2.8 Model fitting and selection

Allometric equations were developed based on individual trees taken through destructive sampling method. The general form model is:

$$yj = f(xi) \quad \text{Equation 3-11}$$

where, yj is biomass of each tree component and the whole above ground tree; xi is forest variables such as tree species, WD, DBH, H, CA, BA, and V.

The modeling was performed applying two main methods: i) Using regression techniques such as linear and linearization from non-linear tested with one or more variables, variables combination, and the least square estimation; ii) non-linear models with one or more variables, variables combination, and Marquardt method. Statistical software including Microsoft Excel, and Stat graphics Centurion were used to construct the models.

It is important to select relevant variables and the optimal model. Methods used to select relevant variables and optimal models of allometric equations are as follows:

- *Coefficients of determination (R^2):* Generally, the highest R^2 value with statistical significance level exhibits the optimal model. However, in some cases, despite the R^2 value being high, the model is not optimal. Therefore, involving additional indicators becomes necessary.
- *T-test for testing the significance of estimates of each parameter:* The null hypothesis Ho: bi = 0, the hypothesis is not accepted; when $P < 0.05$; this indicates the significance of estimates of each parameter. This test is applied for multiple-regression.
- Correction factor(CF) = $\exp(RSE^2/2)$, CF is always >1. Where RSE is Residual standard error. The higher RSE, the bigger CF obtained. This indicates a model with low reliability. The optimum is when CF reaches1. The response y of the models is required to be homogeneous when using this factor to compare models (Chave et al., 2005).
- Mallow's Cp (1973):This is used to select the number of the most relevant variables in case of unclear affects of some independent to dependent variable y. The Cp is as close to variable p the model is as consistent. This can be used as the basis for determining the p variables involved when there are multiple variables assumed to have an impact.
- *Akaike Information Criterion(AIC)*:AIC is used to select the optimal model with several predictors. In the general case, the AIC is:

[2] Data file: Database for AE development Quang Nam – TNU, sheet: 110 tree data.

[3] Data of 90 trees: Database for AE development Quang Nam – TNU, in sheet: 90 trees for AE and 20 tree for assessing in ssheet: 20 trees for validation.

$$AIC = n * \ln\left(\frac{RSS}{n}\right) + 2K = -\ln(L) + 2K \qquad \text{Equation 3-12}$$

where, K is the number of parameters in the statistical model (for example: the model y = a +bx, then K = 3); L is the maximized value of the likelihood function for the estimated model; n is number of observations; and RSS is the residual sums of squares. The optimal model will minimize the AIC algebra value (Chave et al., 2005).

- Average deviation between estimated values and observed values (S%):

$$S\% = \frac{100}{n}\sum_{i=1}^{n}\frac{|\mathrm{Yilt} - \mathrm{Yi}|}{\mathrm{Yi}} \qquad \text{Equation 3-13}$$

where, Yilt is predicted value; Yi is observed value; n is number of observations. S% denotes how well the model fits the actual data. The model is optimal when S% is minimum. S% is calculated in two cases: i) comparing predicted values with observations used to develop the model (S_1%); ii) comparing predicted values to independent observation values (S_2%).In this research, data set from 90 sample trees was used to develop the model, and data from 20 sample trees was employed to evaluate the model (Chave et al., 2005).

Solutions for selection of relevant variable, multivariate, and optimal models:

- *In case of simple variable function, linear multivariate models or non-linear multiple-variable but linearized*: four statistical indicators R^2,CF, AIC, and S% were used to compare and select the optimal model, of which CF and S% are more important. Table 4 is an illustration of using Stat graphics software for selecting optimal model.

Table 3: Detection of variable regression using Statgraphics software (an example for simple Regression Y = AGB vsX = DBH)

Model	Correlation	R-Squared
Multiplicative log(Y) = a + b*log(X)	0.9897	97.94%
Square root-Y Sqrt(Y) = a + b*X	0.9774	95.53%
Logarithmic-Y square root-X log(Y) = a + b*sqrt(X)	0.9749	95.04%
Square root-Y squared-X sqrt(Y) = a +b*X^2	0.9665	93.41%
Squared-X Y = a +b*X^2	0.9531	90.84%
Double square root sqrt(Y) = a +b*sqrt(X)	0.9511	90.47%
Exponential log(Y) = a + b*X	0.9350	87.42%
S-curve model log(Y) = a + b/X	-0.9240	85.38%
Double reciprocal 1/Y = a + b/X	0.9013	81.24%
Square root-Y logarithmic-X	0.8958	80.25%

Sqrt(Y) = a +b*log(X)		
Linear Y = a + b*X	0.8819	77.77%
Logarithmic-Y squared-X log(Y) = a + b*X^2	0.8259	68.21%
Square root-X Y = a + b*sqrt(X)	0.8159	66.57%
Double squared Y^2 = a + b*X^2	0.7869	61.92%
Reciprocal-Y logarithmic-X 1/Y = a + b*log(X)	-0.7504	56.31%
Logarithmic-X Y = a + b*log(X)	0.7293	53.19%
Square root-Y reciprocal-X Sqrt(Y) = a + b/X	-0.7208	51.95%
Squared-Y Y^2 = a + b*X	0.6527	42.61%
Squared-Y square root-X Y^2 = a + b*sqrt(X)	0.5696	32.44%
Reciprocal-X Y = a + b/X	-0.5324	28.34%
Squared-Y logarithmic-X Y^2 = a * b*log(X)	0.4809	23.13%
Reciprocal-Y squared-X 1/Y = a + b*X^2	-0.4063	16.51%
Squared-Y reciprocal-X Y^2 = a +b/X	-0.3201	10.25%

- *In case of multi-variable, linear multiple-variable or non-linear multiple-variable model:* Cp and AIC were used to select relevant variables and potential model. The optimal modes were selected based on $R^2$with parameters of significant P-value <0.05, CF was near to 1 and S% was minimum.
- In cases of comparison and selection among simple-variable,multi-variable, linear multiple-variable or non-linear multiple-variable model but response y transformed such as ln(y), sqrt(y), 1/y: Cp and AIC were used to select number of variables for individual function. The final optimal models selected based on R^2 with parameters were significant at P-value <0.05, CF was near to 1 and S% was minimum.

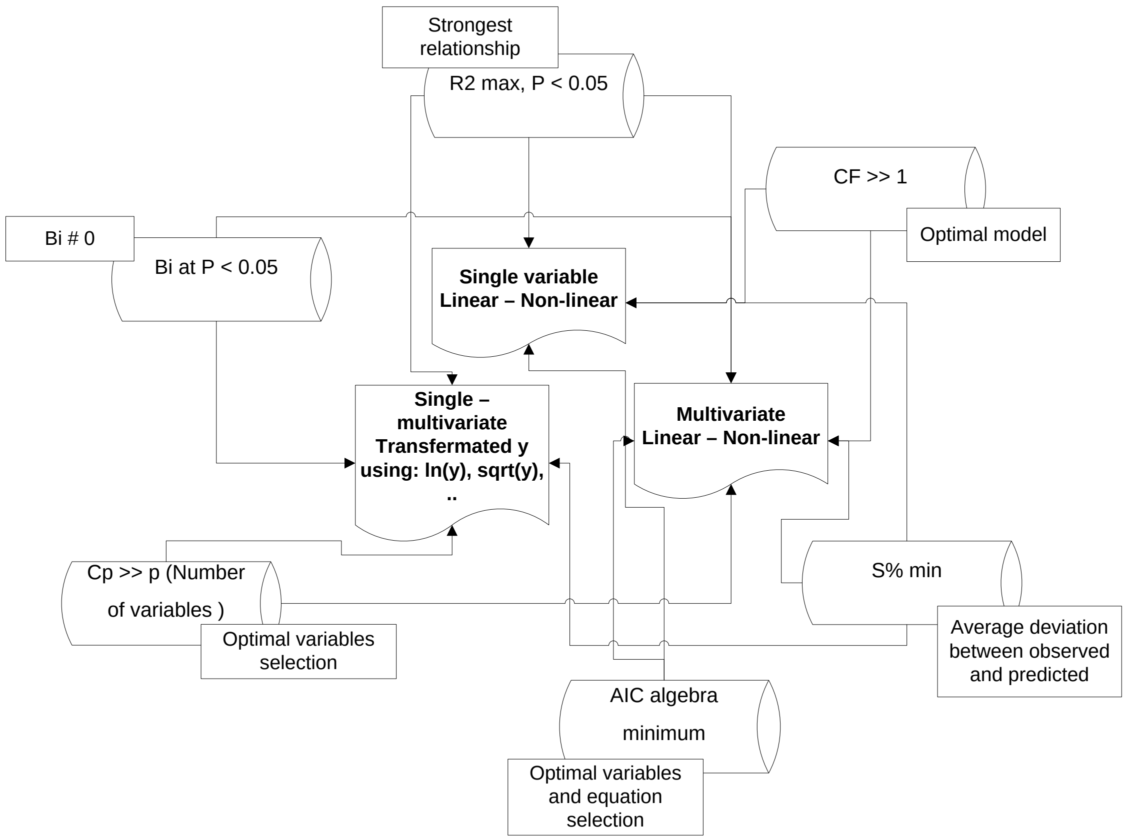


Figure 8: Statistical indicators to compare and select relevant variables and optimal models

3 RESULTS FOR EVERGREEN BROADLEAF FORESTS

3.1 Forest and trees characteristics

3.1.1 Forest characteristics: species composition and forest structure

Species composition

101 tree species from 45 families were found in the two sample plots. The details are presented in Annex 1. IV(%) was used to identify the dominant species (Table 5).

3.1.1.1.1.1.1 Table 4: Ratio of dominant species in study site

Id	Vietnamese name	Scientific name	BA (m^2)	N (tree)	IV(%)
1	Dẻ	Lithocarpus annamensis A. Camus.	11.70	334	14.19
2	Trám	Canarium littorale Bl.	9.30	149	8.79
3	Trâm	Syzygium levinei Merr. Et Perry.	3.13	144	4.96
4	Ngát	Gironiera subaequalis Planch.	2.50	94	3.51
5	Lộc vừng	Barringtonia racenmosa (L.) Spreng	1.95	109	3.50
6	Thị	Diospyros pilosula Hiern.	2.45	86	3.31
7	Giổi	Magnolia braianensis Gagnep.	3.97	34	3.12
8	Trôm	Sterculia parviflora Roxb.	2.11	85	3.09
9	Gội	Aglaia roxburghiana Miq.	2.50	66	2.92
10	Máu chó	Knema pierre Warb.	1.45	92	2.84
	Total of dominant species		41.07	1193	50.24
	81 other species		41.80	1150	49.76
	General total		82.87	2343	100.00

The analysis results of IV showed 10 dominant species with IV>3% and total IV of these species accounted for more than 50% within the stand representing 10% of all species in the stand. The remaining 90% of 91 species represented IV<2% for each species. This indicates that there are few dominant species in the surveyed sites. Although there were many different species of trees in the forest stand, their composition ratios were low, reflecting the diversity and complexity of the species composition of these forests. Consequently, it would involve great amounts of work to develop separate model of biomass estimates by species.

3.1.2 Forest structure

From the measured DBH of sample plots (1ha each), the number of trees were arranged in diameter classes with 10cm intervals, and at the same time, based on the models of H/DBH and V=f(DBH,H) , BA (m^2/ha) and volume M (m^3/ha) within diameter classes were computed for each plot (Table 6, Table 7 ,Figure 9 and Figure 10).

Table 5: Distributions of N/DBH, BA/DBH and M/DBH in sample plot I (SP I)

Mid DBH class (cm)	N/ha	H (m)	BA (m^2/ha)	M (m^3/ha)
10	803	11.3	6.31	41.2
20	229	17.2	7.19	66.5
30	119	21.3	8.41	92.0
40	58	24.5	7.29	88.7
50	23	27.1	4.52	59.4
60	16	29.4	4.52	63.1
70	8	31.3	3.08	45.1
80	6	33.1	3.02	46.0
90	2	34.6	1.27	20.1
100	1	36.1	0.79	12.8
Total	1265		46.39	534.7

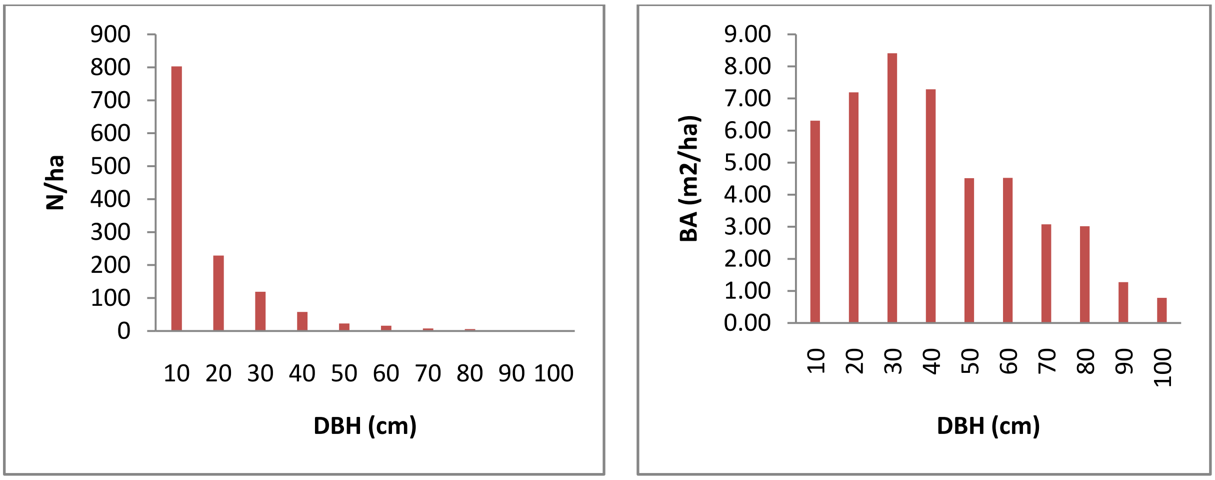


Figure 9: Distributions of N/DBH and BA/DBH in sample plot I

Table 6: Distributions of N/DBH, BA/DBH and M/DBH in sample plot II (SP II)

DBH class middle (cm)	N/ha	H (m)	BA (m^2/ha)	M (m^3/ha)
10	681	11.3	5.35	34.9
20	231	17.2	7.26	67.1
30	77	21.3	5.44	59.5
40	51	24.5	6.41	78.0
50	20	27.1	3.93	51.6
60	6	29.4	1.70	23.7
70	3	31.3	1.15	16.9
80	4	33.1	2.01	30.6

90	0	34.6	0.00	0.0
100	3	36.1	2.36	38.3
Total	1076		35.60	400.6

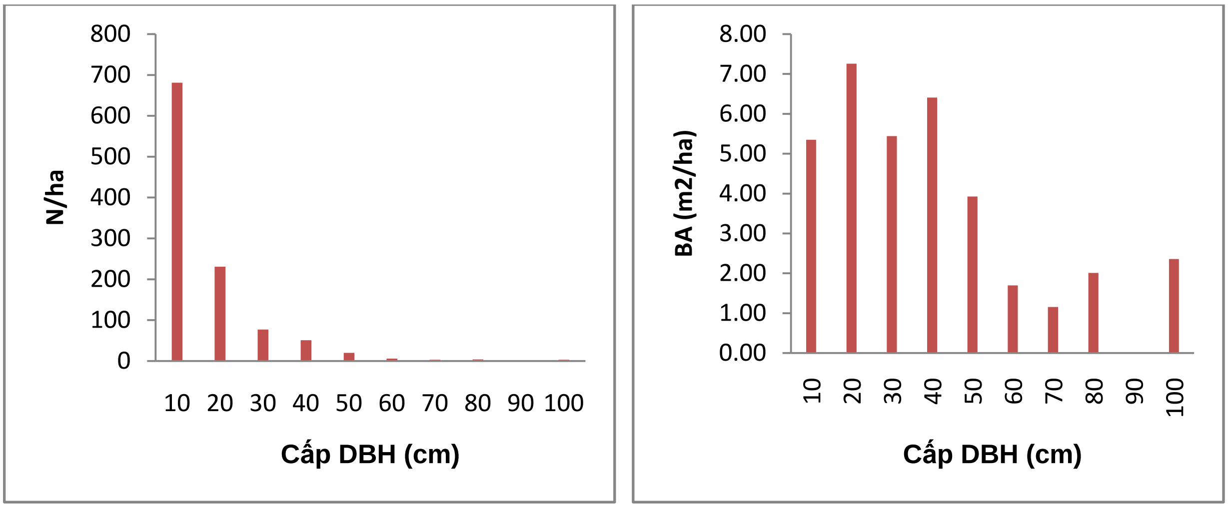


Figure 10: Distributions of N/DBH and BA/DBH in sample plot II

From the distributions of N/DBH, BA/DBH and M/DBH the following are observed:

- Tree density varied from 1076 to 1265 tree/ha (DBH ≥ 5cm).
- N/DBH distribution decreased in inverted J shaped curve from small diameter class to large, exhibiting a stable trend of tree regeneration.
- Stand BA varied from 36 to 46 m^2/ha and M from 400to 535 m^3/ha, exhibiting high volume of forest in the surveyed sites.
- Distributions of BA and M by DBH formed peaks in the diameter class30-40cm. This means above-ground biomass is stored mainly in this diameter class. Therefore, the sampling in the diameter class of 30-40cm will present better biomass models. Additionally, ratio of BA should be consulted in sampling.

3.1.3 Relation between H and diameter

Based on data of sample trees, the relationships among tree variables were constructed.

The optimal model for representing the correlation between H and DBH was tested using the coefficient of determination R^2. The models square root-Y logarithmic-X is selected (Table 8).

Table 7: H-DBH relationship with R^2

Model	Correlation	R squared
Square root-Y logarithmic-X	0.9324	86.94%
Sqrt(Y) = a +b*log(X)		
Square root-X	0.932	86.87%
Y = a + b*sqrt(X)		
Double square root	0.925	85.56%
sqrt(Y) = a +b*sqrt(X)		
Multiplicative	0.923	85.20%

log(Y) = a + b*log(X)		
Logarithmic-X	0.9212	84.87%
Y = a + b*log(X)		
Linear	0.918	84.27%
Y = a + b*X		
Squared-Y	0.9137	83.49%
Y^2 = a + b*X		
Squared-Y square root-X	0.8976	80.56%
Y^2 = a + b*sqrt(X)		
Logarithmic-Y square root-X	0.8971	80.47%
log(Y) = a + b*sqrt(X)		
Double squared	0.8966	80.39%
Y^2 = a + b*X^2		
Square root-Y	0.8947	80.06%
Sqrt(Y) = a + b*X		
S-curve model	-0.8882	78.89%
log(Y) = a + b/X		
Double reciprocal	0.8746	76.50%
1/Y = a + b/X		
Square root-Y reciprocal-X	-0.8618	74.27%
Sqrt(Y) = a + b/X		
Squared-Y logarithmic-X	0.8563	73.32%
Y^2 = a * b*log(X)		
Squared-X	0.8521	72.61%
Y = a +b*X^2		
Exponential	0.8515	72.51%
log(Y) = a + b*X		
Reciprocal-Y logarithmic-X	-0.8388	70.36%
1/Y = a + b*log(X)		
Reciprocal-X	-0.8191	67.09%
Y = a + b/X		
Square root-Y squared-X	0.8064	65.03%
sqrt(Y) = a +b*X^2		
Logarithmic-Y squared-X	0.7447	55.46%
log(Y) = a + b*X^2		
Squared-Y reciprocal-X	-0.71	50.42%
Y^2 = a +b/X		
Reciprocal-Y squared-X	-0.5884	34.62%
1/Y = a + b*X^2		

H-DBH relationship as formula $H = (a + b*\log(DBH))^2$represented below:

$$H = (0.702606 + 1.15182 * \log(DBH))^2 \qquad \text{Equation 4-1}$$

where: R^2 (adjusted) = 86.7921% at $P < 0.0000$; N = 90andStandard Error of Est. = 0.357757; Range of deviation of DBH = 5.0cm – 87.7cm; log: Naperian logarithm

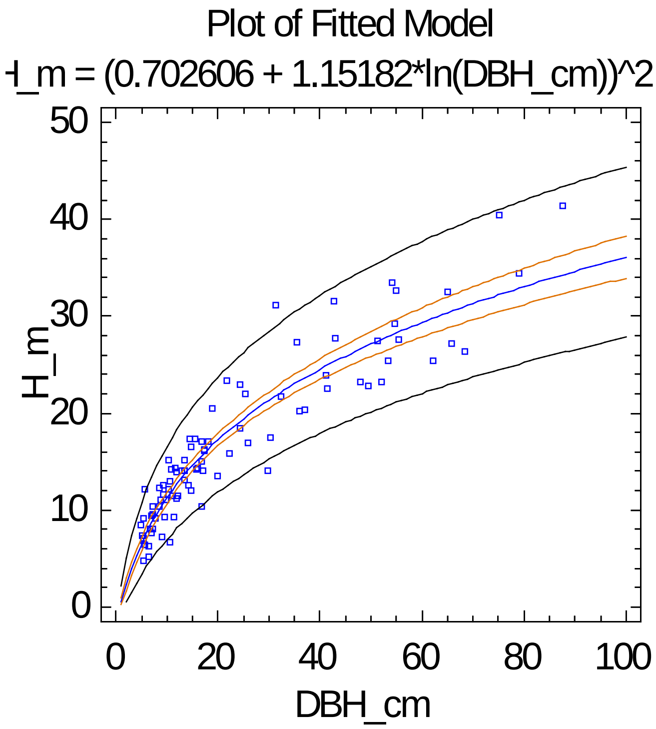


Figure 11: Scattergram of tree height (H) and diameter at breast height (DBH)

3.1.4 Wood density analysis

Biomass and carbon sequestrated in trees depends on tree age, site conditions, and biological characteristics of species. However, due to the complex and diverse nature of tropical forests, where large numbers of species exist but with low frequency of occurrence, development of biomass and carbon models for each species are not a realistic option. Consequently most researchers have developed allometric equations through WD as the representative factor for a specific species group with similar WD (e.g. IPCC 2006, Henry et al., 2010, Chave et al., 2004). WD was calculated as dry oven weight (g) divided by fresh volume (cm^3). Due to differences in species characteristics including growth speed, water content in the wood, and so forth, WD is different among species.

In this study, for the data set of 110 destructively sampled trees, WD was analyzed for all 41 species. The study also tested average deviation of WD by DBH and H of all representative species. Results showed that for all species present in the stand, WD had a very weak relationship with DBH (Figure 12). This is due to the feature of WD; some species exhibited high WD even in small diameters and vice versa. WD depends on tree size within specie, however, each specie occupies a specific forest storey in tropical forests, hence, it is difficult to collect data of all diameters for each species.

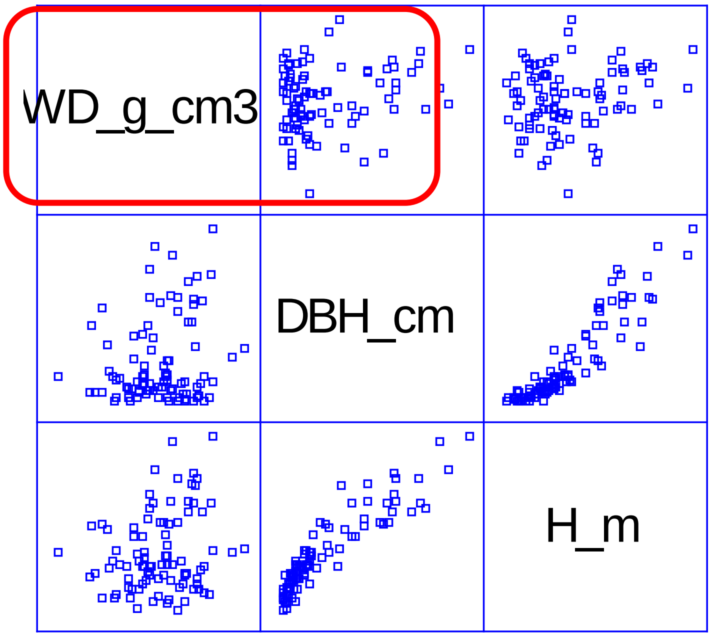


Figure 12: Scattergram of relation between WD and DBH and H, for all species

Table 8: WD descriptive statistics for essential species in the evergreen broadleaf forest in South-Central Coastal Vietnam

	WD (g/cm^3)
Mean	0.586
Standard Error	0.005
Standard Deviation	0.052
Sample Variance	0.003
Kurtosis	-0.012
Skewdness	-0.266
Minimum	0.430
Maximum	0.712
Sum	64.433
Count	110
Confidence Level(95.0%)	0.010

Characteristics of WD of 41 species (Table 9) were found as:

- Skewdness and kurtosis was approximately 0, indicatingthenumberofspecies for WD collected achieved normal distribution, in other words, WD was representative for all tree species of the surveyed sites.
- WD varied between 0.430-0.712, indicating that there was great variation in WD among species. The average WD was 0.586.

- WD was estimated with confident level at 95%: WD = 0.586 ± 0.010

In the forest biomass and carbon estimation models, the WD variable was included as representative for species; when using these models, WD can be determined based on look up table of 41 species (Appendix 2); in cases where specific species data is not available, WD can be estimated using the average WD of 0.586.

3.2 Stem volume

Several models were tested and two selected: the best model with DBH only and the best of DBH and H. Relationships between tree volume (V, m^3) with DBH (cm) only in two models were tested (Table 10).

Table 9: Equations of V with independent variable of DBH only

Equations	R^2 adjusted (%)	P	n	P1	CF	AIC	S_1%	S_2%
log(V_m3) = -8.66352 + 2.46021*log(DBH_cm)	98.493	0.000	90	0.000	1.030	-251.031	18.8%	14.9%
V_m3 = (-0.146495 + 0.0359326*DBH_cm)^2	96.994	0.000	90	0.000	1.008	-366.127	29.9%	21.7%

The results indicate that the following natural logarithm (log) of tree volume model (first model) is the optimal model:

$\log(V) = a + b\log(DBH)$:

log(V_m3) = -8.66352 + 2.46021*log(DBH_cm) Equation 4-2

where, R^2(adjusted) = 98.493%, P < 0.0000; N = 90; Range of DBH = 5.0– 87.7cm; Log: Naperian logarithm

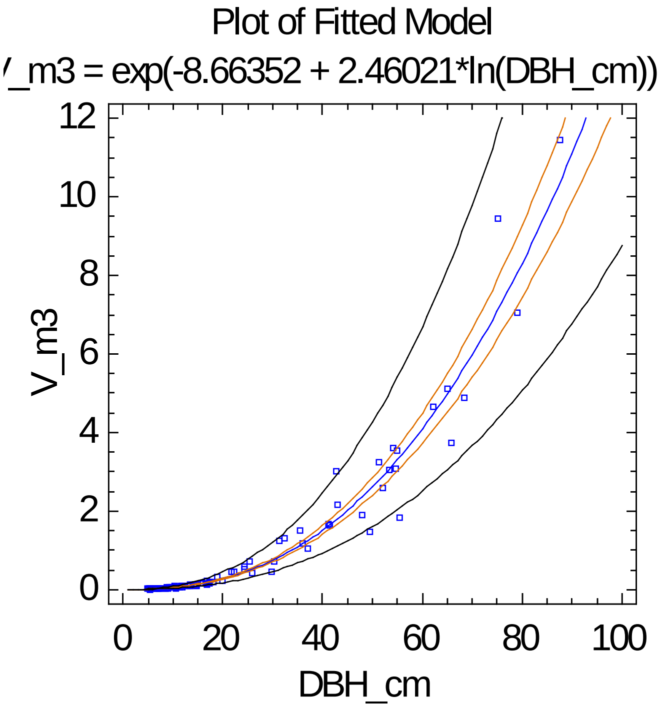


Figure 13: Plot fited model between V and DBH

Relationships between tree volume (V, m^3) with DBH (cm) and H (m) in two models were tested (table 11).

Table 101: Equations of V with independent variable of DBH and H

Equations	R^2 adjusted (%)	P	n	P1	P2	CF	AIC	S_1%	S_2%
log(V) = -9.68839 + 0.956145*log(DBH^2*H)	99.409	0.000	90	0.000	-	1.012	-335.229	11.2	10.0
log(V) = -9.71917 + 1.89407*log(DBH) + 0.986722*log(H)	99.402	0.000	90	0.000	0.000	1.012	-333.364	11.1	10.0

The results indicate that the following natural logarithm (log) of tree volume model (first model) is the optimal model:

$\log(V) = a + b\log(DBH^2*H)$ or $V = c(DBH^2*H)^b$:

$$log(V) = -9.68839 + 0.956145 * \log(DBH^2 * H) \qquad \text{Equation 4-3}$$

where, R^2(adjusted) = 99.409%, P < 0.0000; N = 90and Standard Error Est. = 0.151908; Range of DBH = 5.0– 87.7cm and H = 4.7– 41.4m; Log: Naperian logarithm

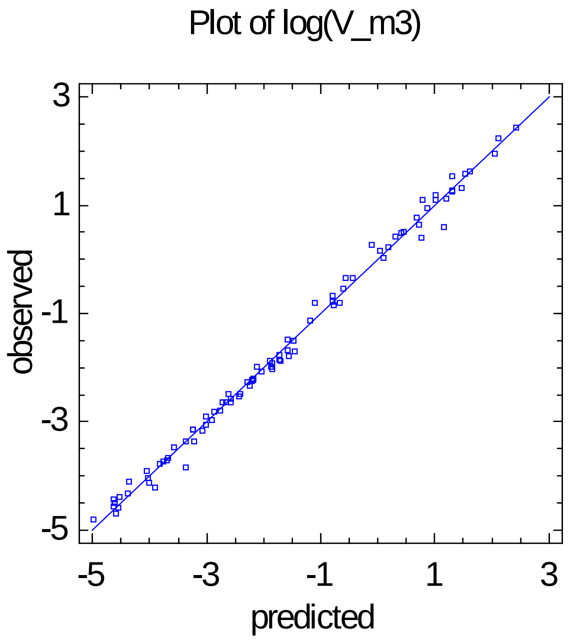


Figure 14: Linear regression between observed V with predicted V of equation V = f(DBH, H)

Comparison of indicator such as S_1% and S_2% of 2 model with DBH only and DBH and H showed that V equation with 2 variables is better with lower average deviation.

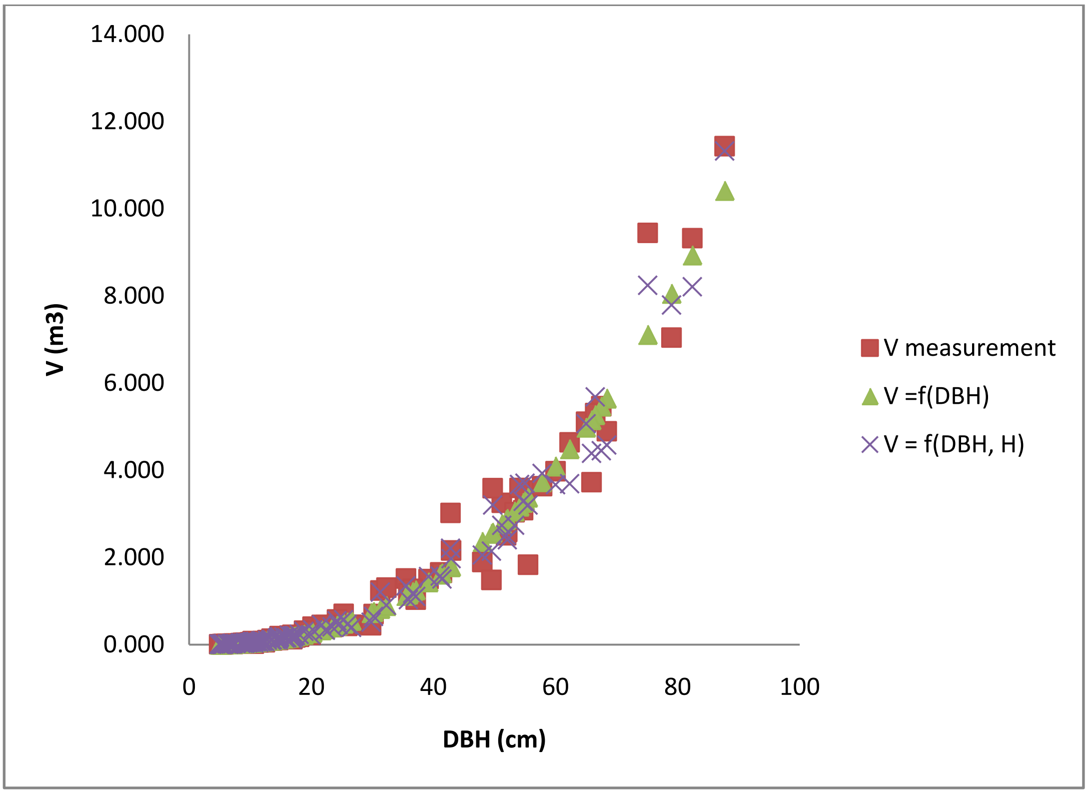


Figure 145: Comparison of V equations by DBH only and DBH and H with V mesurement

3.3 Aboveground biomass

3.3.1 Modeling per tree compartments

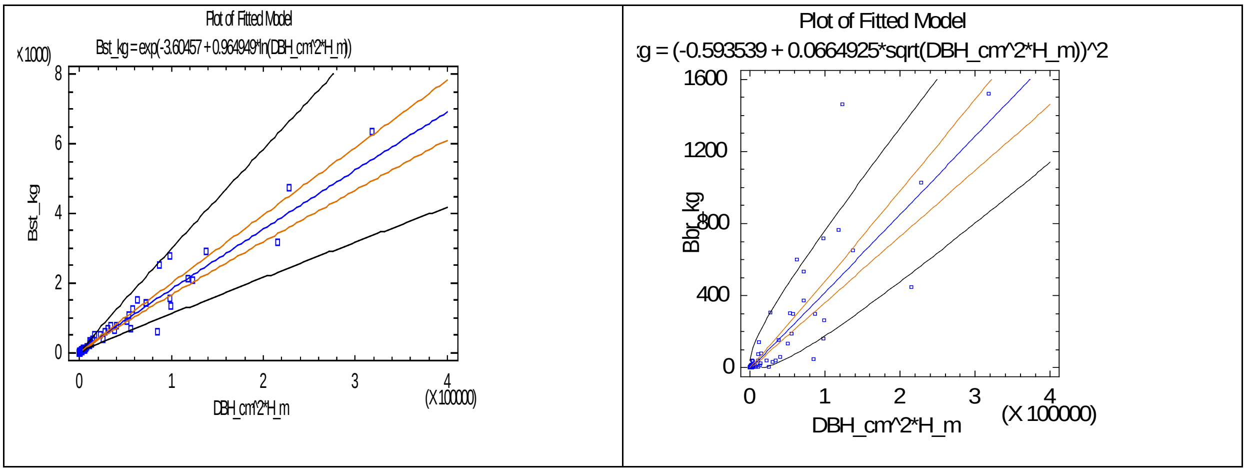
AGB includes the four main tree biomass components of stem (Bst, kg/tree), branch (Bbr, kg/tree), leave (Bl, kg/tree) and bark (Bba, kg/tree). Biomass of each component can be estimated directly through general tree variables such as DBH and H. This study tested the relation between tree biomass components and group of variables DBH^2*H.

Optimal models for each tree biomass component were tested (Table 12). The results show that the model of stems reaches lowest average deviation and next is for bark. The equations to estimate biomass of branches and leaves have higher S% values, indicating estimation of biomass of branches and leaves using separate equations for each component will result in high uncertainty.

Table 112: Equations of four biomass components by DBH and H

	R^2 adjusted (%)	P	N	Pi	CF	AIC	S_1%	S_2%
log(Bst) = -3.60457 + 0.964949*log(DBH^2*H)	98.493	0.000	90	0.000	1.031	-248.561	19.4	18.1
Bbr = (-0.593539 + 0.0664925*sqrt(DBH^2*H))^2	84.035	0.000	90	0.000	478.785	230.152	118.2	61.1
Bl = (0.66048 + 0.0160822*sqrt(DBH^2*H))^2	78.481	0.000	90	0.000	1.683	7.602	74.3	86.9
log(Bba) = -5.42418 + 0.918678*log(DBH^2*H)	94.874	0.000	90	0.000	1.101	-143.917	36.4	28.8

Remark: log: Naperian logarithms; Pi: p-value for each factor i



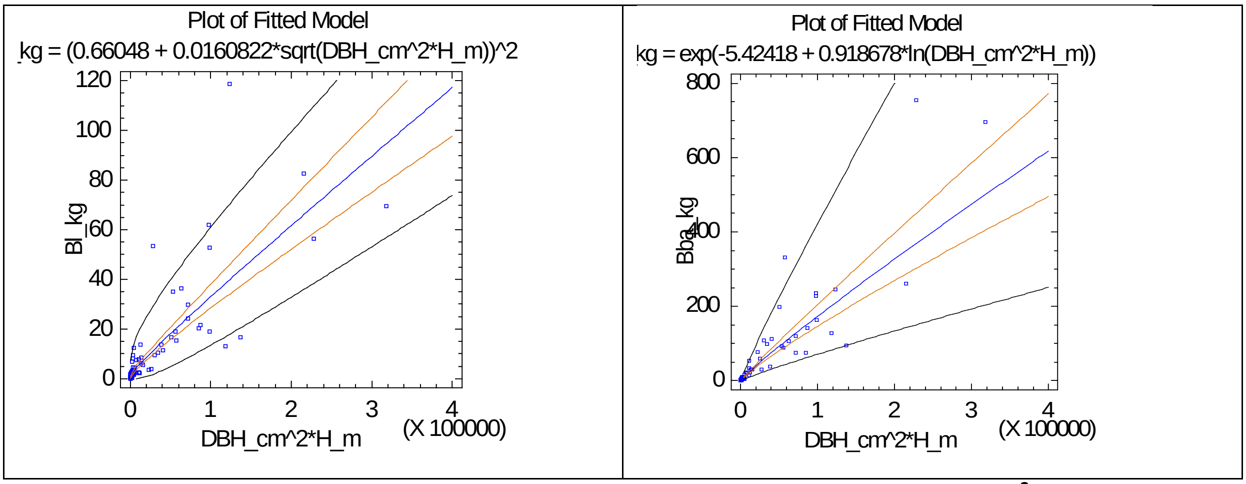


Figure 156: Fitted model of biomass of 4 components with variable DBH^2 and H

3.3.2 Modeling of total aboveground biomass (AGB)

The predictors for AGB estimate were mainly DBH and H in research by Brown (1989-2001) and Brown and Iverson (1992); some authors used WD (e.g. Chave et al. (2005), Basuki et al. (2009). Furthermore some authors suggested that the variable CA helps to improve accuracy and reliability of the model; e.g. Henry et al., (2010),Dietz et al.,(2011), and Johannes et al.,(2011).

Some authors used parabolic of higher order for estimating AGB;e.g.Brown et al.,(2009), Chave (2005), Basuki et al.,(2009))and compared parabolic equation with power and indicated that the lower S(%) of power equation was found.

Biomass estimates for Vietnam limited. Brown(1989-2001)used a totalof371sampletrees for developing biomass models for tropical forest types, including dry forests of India (28 trees), and tropical moist forests (170trees).

AGB has biological relationship with one or more forest variables. Nevertheless, required reliability and available resources will determine the choice of variables possible for application. For this reason, this study tested the relationships between AGB and other forest variables to find other possible models for application.

Descriptive statistics of 90 sample trees are shown in Table 13.

Table 123: Descriptive statistics of variables

Statistics indicators	AGB_{tree}(kg)	DBH(cm)	H(m)	WD(g/cm^3)	CA(m^2)
Observations	90	90	90	90	90
Mean	716.301	23.9244	16.8789	0.582981	22.4194
Standard Deviation	1438.2	20.2309	8.33851	0.0520285	28.4111
Sample Variance	200.781%	84.5618%	49.402%	8.92455%	126.726%
Minimum	6.16691	4.9	4.7	0.4305	0.785398
Maximum	8633.01	87.7	41.4	0.71171	201.062
Stnd. skewness	12.5589	5.04485	3.46337	-0.968168	13.2202
Stnd. kurtosis	24.3082	1.49202	0.46577	0.108	33.1402

Variables of AGB, DBH, H and CA appeared not to follow a normal distribution with standard skewdness or standardkurtosis outside the range of -2 and +2 (Table 13). Hence in order to make these variables more normal, a transformation log was used (Table 14).

Table 134: Normalization of variables

Statistical indicators	log(AGBtree)	log(DBH)	log(H)	WD	log(CA)
Observations	90	90	90	90	90
Mean	4.82031	2.85414	2.70745	0.582981	2.54592
Standard Deviation	1.99262	0.79689	0.495359	0.0520285	1.07551
Sample Variance	41.3381%	27.9205%	18.2962%	8.92455%	42.2447%
Minimum	1.8192	1.58924	1.54756	0.4305	-0.241564
Maximum	9.06335	4.47392	3.72328	0.71171	5.30361
Stnd. skewness	1.31621	1.25513	-0.240832	-0.968168	0.332395
Stnd. kurtosis	-1.871	-1.95495	-1.13924	0.108	-0.671572

With DBH only

Alternative models were compared to obtain the optimum, using the coefficient R-squared (R^2) to determine selection of equation.

Table 145: Alternative models of AGB and DBH relation

Model	Correlation	R-Squared
Multiplicative log(Y) = a + b*log(X)	0.9897	97.94%
Square root-Y Sqrt(Y) = a + b*X	0.9774	95.53%
Logarithmic-Y square root-X log(Y) = a + b*sqrt(X)	0.9749	95.04%
Square root-Y squared-X sqrt(Y) = a +b*X^2	0.9665	93.41%
Squared-X Y = a +b*X^2	0.9531	90.83%
Double square root sqrt(Y) = a +b*sqrt(X)	0.9511	90.46%
Exponential log(Y) = a + b*X	0.935	87.42%
S-curve model log(Y) = a + b/X	-0.924	85.38%
Double reciprocal 1/Y = a + b/X	0.9013	81.23%
Square root-Y logarithmic-X	0.8958	80.24%

Sqrt(Y) = a +b*log(X)		
Linear	0.8818	77.76%
Y = a + b*X		
Logarithmic-Y squared-X	0.8259	68.21%
log(Y) = a + b*X^2		
Square root-X	0.8158	66.55%
Y = a + b*sqrt(X)		
Double squared	0.7868	61.90%
Y^2 = a + b*X^2		
Reciprocal-Y logarithmic-X	-0.7503	56.30%
1/Y = a + b*log(X)		
Logarithmic-X	0.7292	53.17%
Y = a + b*log(X)		
Square root-Y reciprocal-X	-0.7207	51.94%
Sqrt(Y) = a + b/X		
Squared-Y	0.6526	42.59%
Y^2 = a + b*X		
Squared-Y square root-X	0.5695	32.43%
Y^2 = a + b*sqrt(X)		
Reciprocal-X	-0.5323	28.33%
Y = a + b/X		
Squared-Y logarithmic-X	0.4808	23.12%
Y^2 = a * b*log(X)		
Reciprocal-Y squared-X	-0.4063	16.51%
1/Y = a + b*X^2		
Squared-Y reciprocal-X	-0.32	10.24%
Y^2 = a +b/X		

As in Table 15, Multiplicative and Square root-Y were selected. AGB was then estimated based on the two selected models (Table 16);

Table 156: Equations of AGB with independent variable of DBH

Equation	R^2 adjusted (%)	P	n	Pi	CF	AIC	S_1%	S_2%
AGB_{tree} = exp(-2.24267 + 2.47464*ln(DBH))	97.919	0.000	90	0.000	1.042	-220.434	23.0	15.1
AGB_{tree} = (-4.34247 + 0.947556*DBH)^2	95.478	0.000	90	0.000	5988.140	261.035	35.0	30.0

Remark: Pi: p-value for each factor i.

On comparing the two models above, the optimal results was generated through the following (first) model:

$AGB = c*DBH^b$ or

$\log(AGB) = a + b*\log(DBH)$ or

$AGB = \exp(a + b*\log(DBH)$:

$$AGB_{tree} = \exp(-2.24267 + 2.47464 * \ln(DBH)) \quad \text{Equation 4-4}$$

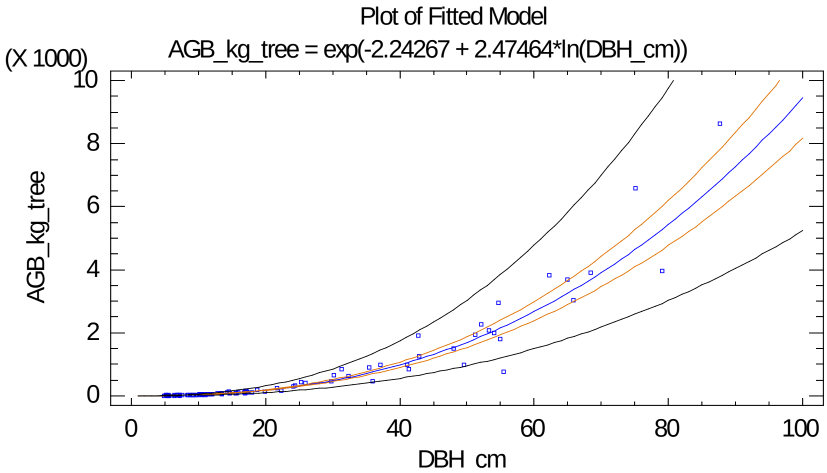


Figure 167: Relationship between AGB and DBH using the multiplicative model

The selected equation was compared to that of Brown (1997), developed for tropical moist forests based on the data collected by several authors from different tropical countries and at different times (Figure 18);

The allometric equation published by Brown (1997) is:

$$AGBtree = \exp(-2.134 + 2.530 * \ln(DBH)) \quad \text{Equation 4-5}$$

DBH=5-148cm, n=170 trees, R^2=0.970

Table 167: Comparison of Brown (1997) with selected equation for DBH

	S_1%	S_2%
Brown (1997)	39.9	39.9
Equation 4-4	23.0	15.1

The equation developed for this area is more suitable than the equation of Brown (1997). The equation from the current study reduced average deviation (S%) by 16-24% as compared to the equation of Brown (1997).

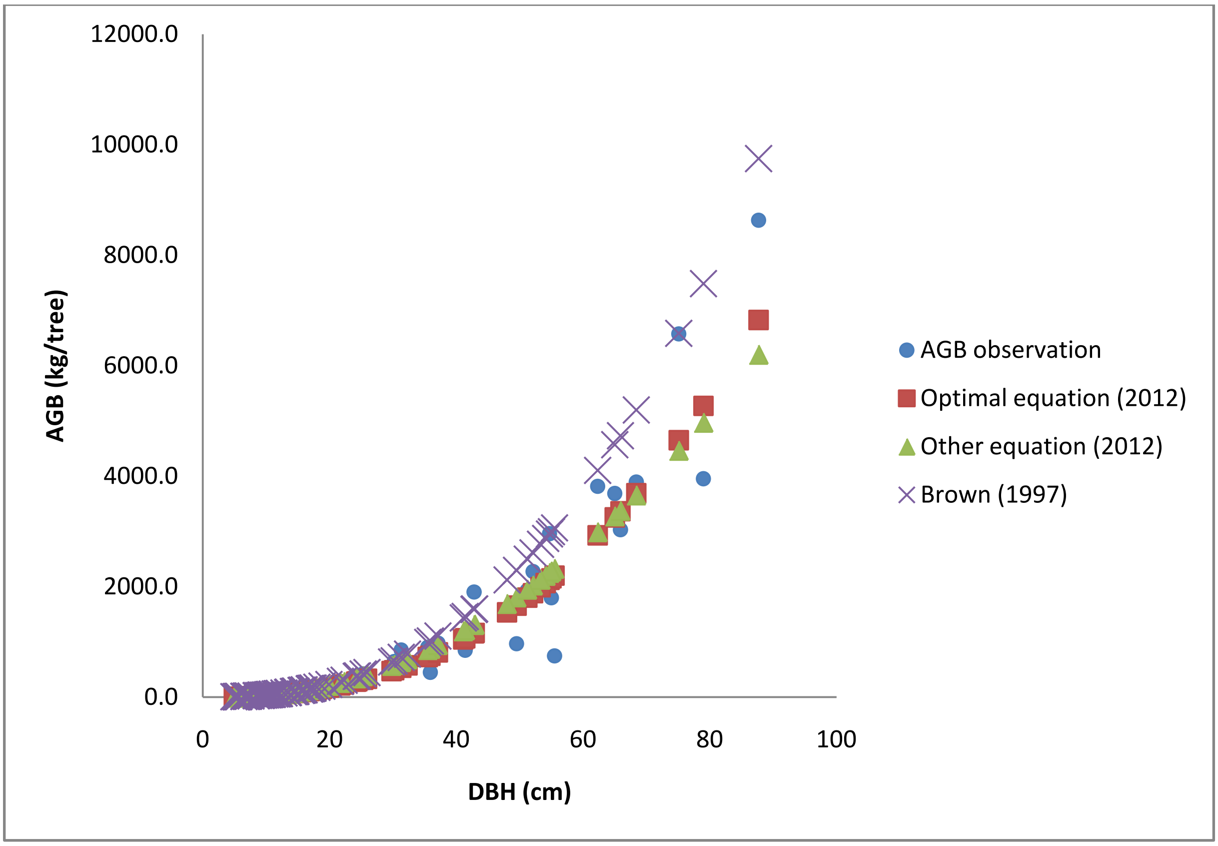


Figure 178: Comparison of equations from this study and equations of Brown (1997)

With all explanatory variables

Relationship of AGB with DBH and H

The difference of tree height (H) among diameter classes is due to some factors such as biological characteristics of species and site conditions. Therefore, adding variable H in the model was expected to improve the accuracy of the model.

Alternative models were compared to obtain the optimal (table 18).

Table 178: Models of AGB estimate by DBH and H

Equation	R^2 adjusted (%)	P	n	Pi	CF	AIC	S_1%	S_2%
$\log(AGB_{tree}) = -2.87966 + 2.13303*\log(DBH) + 0.595399*\log(H)$	98.227	0.000	90	0.000	1.036	-233.872	21.4	15.6
$\log(AGB_{tree}) = -3.24286 + 0.958201*\log(DBH^2*H)$	98.124	0.000	90	0.000	1.038	-229.772	22.1	16.3

Remark: log: Naperian logarithm; Pi: p-value for each factor i

On comparing the two equations above, the optimal result for estimation of ABG was generated through the following (first) equation:

$$\log(AGB_{tree}) = -2.87966 + 2.13303 * \log(DBH) + 0.595399 * \log(H) \quad \text{Equation 4-6}$$

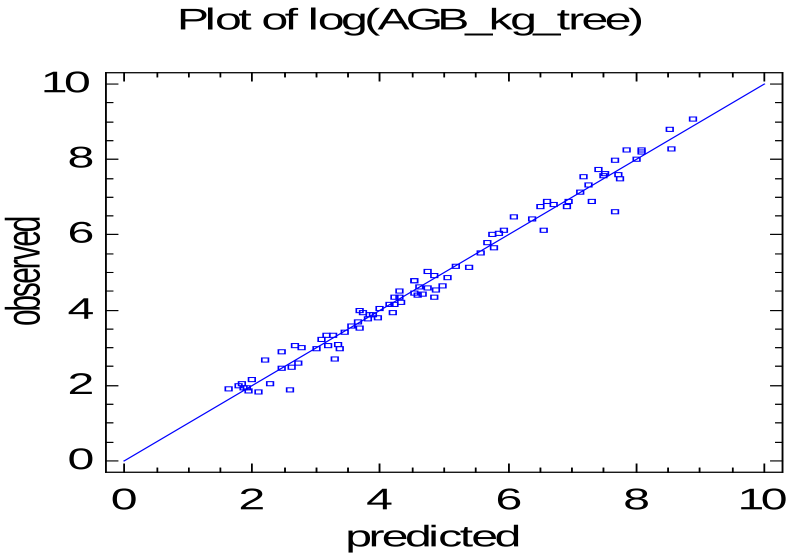


Figure 189: AGB predicted plotted against observed AGB

Relationship of AGB with DBH, H and WD

Biomass content may be different even for the same tree of the same DBH class and H. This is due to biological characteristics of the species. While it is difficult to develop models for each species in tropical forests, the variable WD is considered as a representing factor, reflecting dry biomass stored in different species.

Relationship between AGB with three variables of DBH, H and WD was examined through alternative models to obtain the optimal (Table 19).

Table 189: Estimation of AGB from DBH, H and WD

Equation	R^2 adjusted (%)	P	N	Pi	CF	AIC	S_1%	S_2%
$\log(AGB_{tree})$ = -2.06535 + 2.14325*log(DBH) + 0.543595*log(H) + 1.29354*log(WD)	98.551	0.000	90	0.000	1.029	-251.632	18.3	13.5
$\log(AGB_{tree})$ = -2.68198 + 0.953025*log(DBH^2*H*WD)	98.423	0.000	90	0.000	1.032	-245.381	19.6	15.6

Remark: log: Naperian logarithm; Pi: p-value for each factor i

Comparing the two equations above, the optimal result for estimation of AGB was generated through the following (first)equation:

$$log(AGB_{tree}) = -2.06535 + 2.14325 * \log(DBH) + 0.543595 * \log(H) + 1.29354 * \log(WD)$$ Equation 4-7

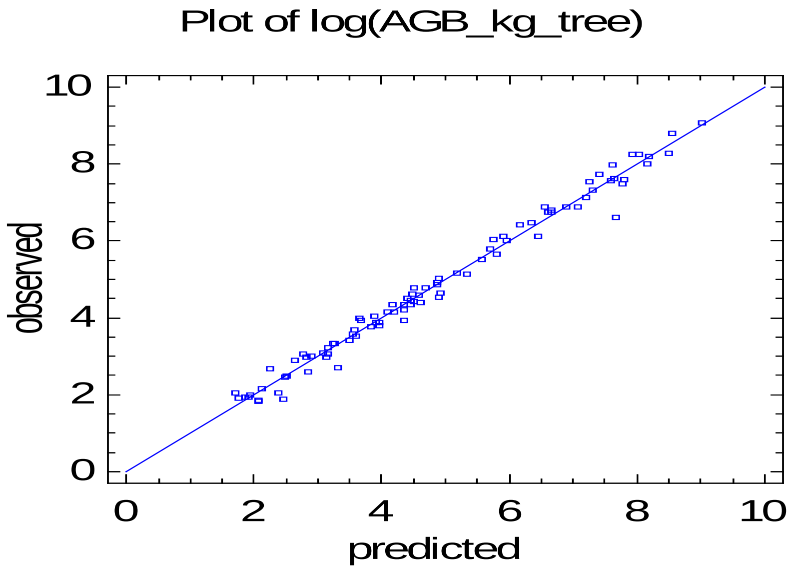


Figure 20: AGB predicted (from DBH, H and WD) plotted against observed AGB

Equation 4-7 was compared to that of Chave (2005) for which S% = 52-94%, and model for dry dipterocarp forest by Basukiet et al. (2009) for which S% = 26-30%. With the Equation 4-6, average deviation was significantly reduced (ie. S% = 18.3-13.5%).

The equation published by Chave (2005) developed for tropical forests in America, Asia, and Oceania is:

$$\langle AGB \rangle_{est} = \exp\left(-2.977 + \ln\left(\rho D^2 H\right)\right) \equiv 0.0509 \times \rho D^2 H$$ Equation 4-8

Using data from this study to apply to both equations, S% was reduced by 5-9% by use of the model of the current study (Table 20).

Table 20: Comparison of Chave (2005) with selected equation for DBH, H and WD

	S_1%	S_2%
Equation 4-8 Chave (2005)	23.6	22.7
Equation 4-7	18.3	13.5

Relationship of AGB with DBH, H and CA

To improve accuracy of the model, variable crown area (CA) was added. In fact, CA and branch are vary greatly due to morphological characteristics of each species; for instance, for trees with similar

DBH, H and WD, it is easy to assume the same average biomass of the stem, while branches and foliage, which account for a significant portion, appear apparently different because of their diverse morphological features on different site conditions and terrain. As a result, addition of the CA variable may improve reliability of estimates, taking into account that establishing allometric equations for each specie and condition of tropical forests is not a realistic option.

Relationship of AGB with variables DBH, H and CA, was examined through alternative models (Table 21).

Table 191: Models of AGB estimate by DBH, H and CA

Models	R^2 adjusted (%)	P	n	Pi	CF	AIC	S_1%	S_2%
$\log(AGB_{tree})$ = -2.88451 + 1.83767*log(DBH) + 0.73632*log(H) + 0.183159*log(CA)	98.437	0.000	90	0.000	1.032	-244.284	19.5	14.7
$\log(AGB_{tree})$ = -2.88418 + 0.735931*log(DBH^2*H) + 0.18307*log(DBH^2*CA)	98.455	0.000	90	0.000	1.031	-246.284	19.5	14.7

Remark: log: Naperian logarithms; Pi: p-value for each factor i

Both models obtained similar statistical indicators (Table 4-15). However the following (second)model is selected for having a higher coefficient of determination.

$$\log(AGB_{tree}) = -2.88418 + 0.735931 * \log(\mathrm{DBH}^2 * \mathrm{H}) + 0.18307 * \log(\mathrm{DBH}^2 * \mathrm{CA})$$ Equation 4-9

S% did not change much from that of the WD equation (i.e. S_1% = 18.3% and S_2% = 13.5%). However, it is important to note that CA data is easier to collect in the field as compared to WD data. From this equation, S_1% = 19.5% and S_2% = 14.7%.

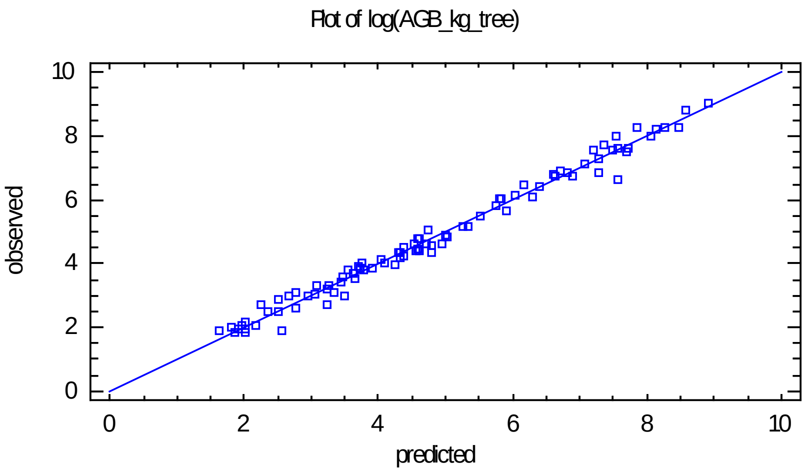


Figure 21: The linear regression between observed AGB with the model

Relationship of AGB with DBH, H, WD and CA

All four variables of DBH, H, WD and CA affect AGB. The four variables together are able to account for AGB reflecting tree size and biological characteristics of species in different site conditions. Relationships between AGB with these variables were tested to select potential models (Table 22).

Table 202: Equations of AGB by DBH, H, WD and CA

equation	R^2 adjusted (%)	P	n	Pi	CF	AIC	S_1%	S_2%
$\log(AGB_{tree})$ = -2.23222 + 0.744261*log(DBH^2*H) + 1.13674*log(WD) + 0.17046*log(DBH^2*CA)	98.710	0.000	90	0.000	1.026	-261.550	17.2	13.4
$\log(AGB_{tree})$ = -2.15082 + 1.89583*log(DBH) + 0.666612*log(H) + 1.16199*log(WD) + 0.152338*log(CA)	98.701	0.000	90	0.000	1.026	-259.972	17.2	13.0

Remark: log: Naperian logarithms; Pi: p-value for each factor i

Table 22 indicates both models obtained rather similar statistical indicators. However the following (first) models was selected for having a higher coefficient of determination.

$$\log(\text{AGBtree}) = -2.23222 + 0.744261 * \log(\text{DBH}^2 * \text{H}) + 1.13674 * \log(\text{WD}) + 0.17046 * \log(\text{DBH}^2 * \text{CA})$$ Equation 4-10

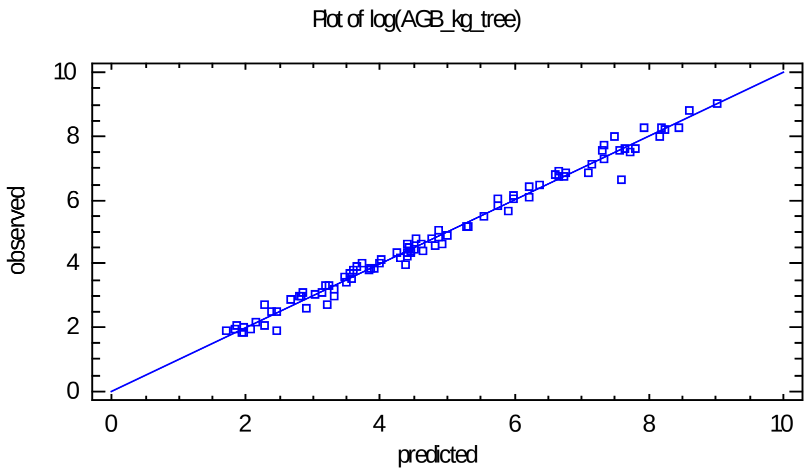


Figure 192: The linear regression between observed AGB with the model

Comparison of AGB estimations of different forest variables

In the above sections, five AGB models were developed using one or more variables. S_2% was employed as an indicator to compare the models (Table 23).

Table 213: Comparison deviation of the models of different number of variables

Function form	Equation	R^2 adjusted (%)	CF	AIC	S_2%
AGB = f(DBH)	Equation 4-4	97.919	1.042	-220.434	15.1
AGB = f(DBH, H)	Equation 4-6	98.227	1.036	-233.872	15.6
AGB = f(DBH, H, WD)	Equation 4-7	98.551	1.029	-251.632	13.5
AGB = f(DBH, H, CA)	Equation 4-9	98.455	1.031	-246.284	14.7
AGB = f(DBH, H, WD, CA)	Equation 4-10	98.710	1.026	-261.550	13.4

Remark: log: Naperian logarithm;

The general observation of the results is that the increase in the number of independent variables from one to four reduced average deviation of the AGB estimates, indicating all four variables of DBH, H, WD and CA affect AGB, of which DBH and H reflect the relationship between the tree volume and biomass, while WD and CA reflect biological characteristics of species. The lowest deviation was with the model involving four variables with S_2% =13.4%. Compared with general AGB models available for tropical forests, (i.e. model of Brown (1997)had S%=43-107%, ;model of Chave (2005) had S% = 52-94% and model for dry dipterocarp forests of Basukiet et al.,(2009) had S%=26-30%, the model with four variables applied for each forest type in different ecological regions has the potential to bring highest reliability. However, a practical concern is that, with more variables, its application becomes more complex and costly.

Although Equation 4-4 with only the DBH predictor had a high deviation value, and the lowest coefficient of determination, the model may still be acceptable as S_2=15.1%. This model can be applied in the case of a rapid inventory or inventory methods involving grass roots actors such as community because of its facility in practical aspects.

A higher R^2 with S_2% = 15.6% was found in Equation 4-6 with two variables of DBH and H, with applicability particularly for cases of variation of H within H classes when site conditions change.

Equation 4-9 or Equation 4-10 applying three variables of DBH, H, WD or CA helped to reduce deviation. This reflects the biological characteristics of tree species on WD and CA, of which CA is easier to measure. Adding the CA variable to DBH and H does not significantly impact survey costs as CA is easy to measure.

Estimation of AGB from standing tree volume (V)

The forest inventory system employed in Vietnam in the past has traditionally measuredcommercial tree volume (V), therefore can be used for converting to AGB. A range of alternative models were compared to estimate AGB using (V), using the coefficient R-squared (R^2) to determine selection of equation.

Multiplicative and Linear were selected (Table 24).

Table 224: Comparison of Alternative Models of AGB and V

Model	Correlation	R-Squared
Multiplicative	0.9931	98.62%
log(Y) = a + b*log(X)		
Linear	0.987	97.41%
Y = a + b*X		
Double squared	0.986	97.23%
Y^2 = a + b*X^2		
Double reciprocal	0.9696	94.01%
1/Y = a + b/X		
Square root-Y	0.9455	89.39%
Sqrt(Y) = a + b*X		
Square root-X	0.9239	85.36%
Y = a + b*sqrt(X)		
Squared-X	0.9152	83.76%
Y = a +b*X^2		
Logarithmic-Y square root-X	0.9147	83.67%
log(Y) = a + b*sqrt(X)		
Square root-Y logarithmic-X	0.8961	80.30%
Sqrt(Y) = a +b*log(X)		
Squared-Y	0.8853	78.38%
Y^2 = a + b*X		
Exponential	0.7616	58.00%
log(Y) = a + b*X		
Square root-Y squared-X	0.7583	57.51%
sqrt(Y) = a +b*X^2		
Logarithmic-X	0.7306	53.38%
Y = a + b*log(X)		
Squared-Y square root-X	0.7194	51.76%
Y^2 = a + b*sqrt(X)		
Logarithmic-Y squared-X	0.5179	26.82%
log(Y) = a + b*X^2		
Square root-Y reciprocal-X	-0.4964	24.64%
Sqrt(Y) = a + b/X		
Squared-Y logarithmic-X	0.4859	23.61%
Y^2 = a * b*log(X)		
Reciprocal-X	-0.3324	11.05%
Y = a + b/X		
Squared-Y reciprocal-X	-0.1872	3.50%
Y^2 = a +b/X		

Table 235: Equations of AGB by V

	R^2 adjusted (%)	P	n	Pi	CF	AIC	S_1%	S_2%
$\log(AGB_{tree})$ = 6.46499 + 1.00179*log(V)	98.605	0.000	90	0.000	1.028	-256.426	18.9%	16.8%
AGB_{tree} = -25.374 + 708.243*V	97.383	0.000	90	0.000	#NUM!	984.916	79.7%	60.3%

Remark: log: Naperian logarithm; Pi: p-value for each factor i

On comparing the two models above, the results show similar statistical indicators (Table 25). However the following (first)model was selected for having a higher coefficient of determination and lower average deviation S%.

$\log(AGB) = a + b*\log(V)$ or $AGB = c*V^b$:

$$\log(AGBtree) = 6.46499 + 1.00179 * \log(V) \quad \text{Equation 4-34}$$

This model had lowest S1% = 18.9% and S2% = 16.8%.

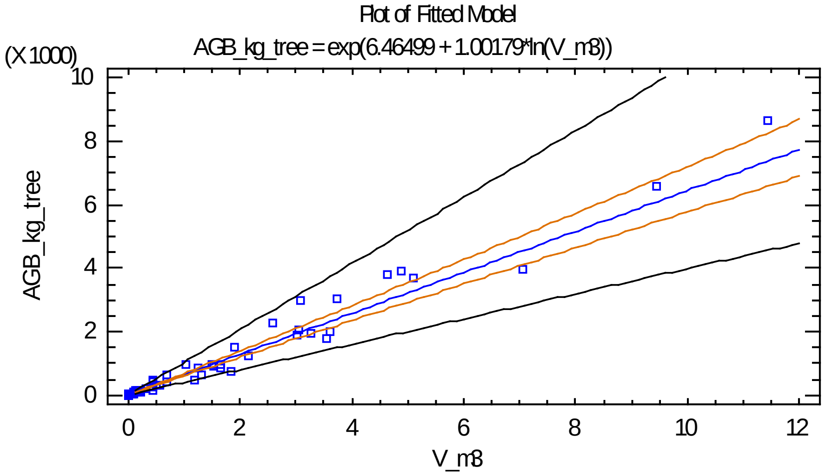


Figure 203: Fitted model between observed AGB and V

3.3.3 Modeling of ABG for the main tree families and species

For the total sample of 110trees including 41 species and 29 families of plants, relational analysis (Figure 24) indicates that the AGB is closely related to plant family. However, with the limited number of trees felled in this study (maximun 11 trees felled per family), designing AGB equations for each plant family was not possible. It is recommended that further studies look into such model development with adequate numbers of sample trees. Therefore this study focused on developing models to estimate AGB for all plant species with variables DBH, H, WD, CA and V.

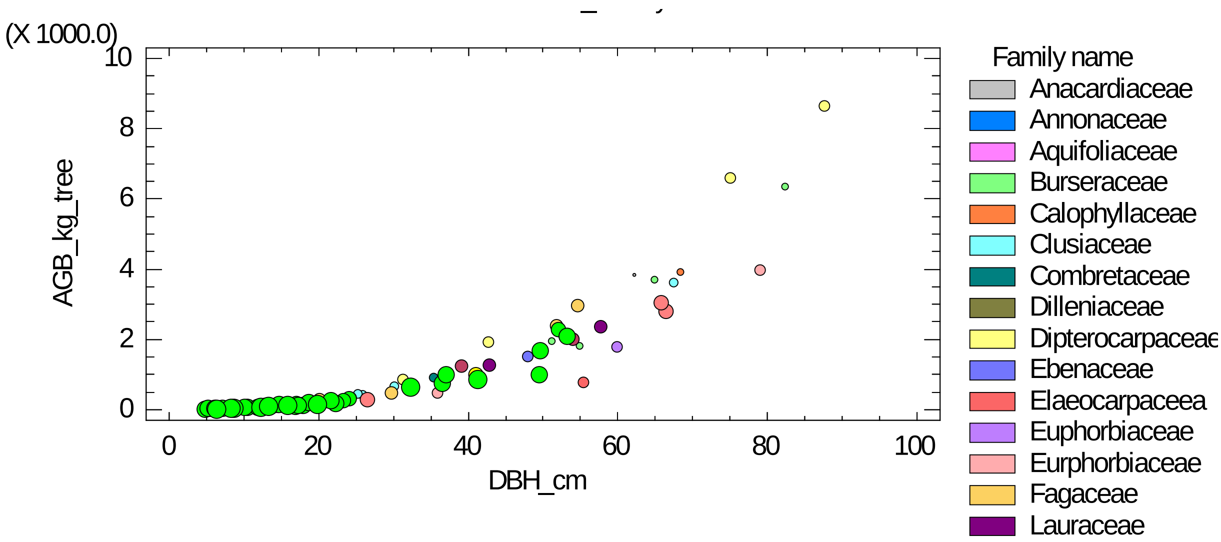


Figure 214: Relationship between AGB and DBH by plant family

3.3.4 Comparison with generic models

Comparison of selected models to the general models of Brown (1997) and Chave et al. (2005) was attempted. To do this, AGB for each of sample trees was calculated following models of Brown and Chave and Equation 4-3andEquation 4-9, then plotted.

Model of Brown (1997) (“Brown, 2001 AGB=f(DBH)”):

$$AGB_{tree} = \exp(-2.134 + 2.530 * \ln(DBH)) \quad \text{Equation 4-41}$$

Model of Chave (2005) with WD, H and DBH as variable (“Chave I, 2005 AGB=f(DBH, H, WD)”:

$$AGB_{tree} = \exp(-2.977 + \log(WD * DBH^2 * H) \quad \text{Equation 4-52}$$

Model of Chave 2005 with WD and DBH as variable (“Chave II, 2005 AGB=f(DBH,WD)”):

$$AGB_{tree} = WD * \exp(-1.499 + 2.148 * \log(DBH) + 0.207 * (\log(DBH))^2 - 0.0281 * (\log(DBH))^3) \quad \text{Equation 4-63}$$

This input provided a strong argument to determine if the use of local AE is more accurate than generic equations (Figure 25).

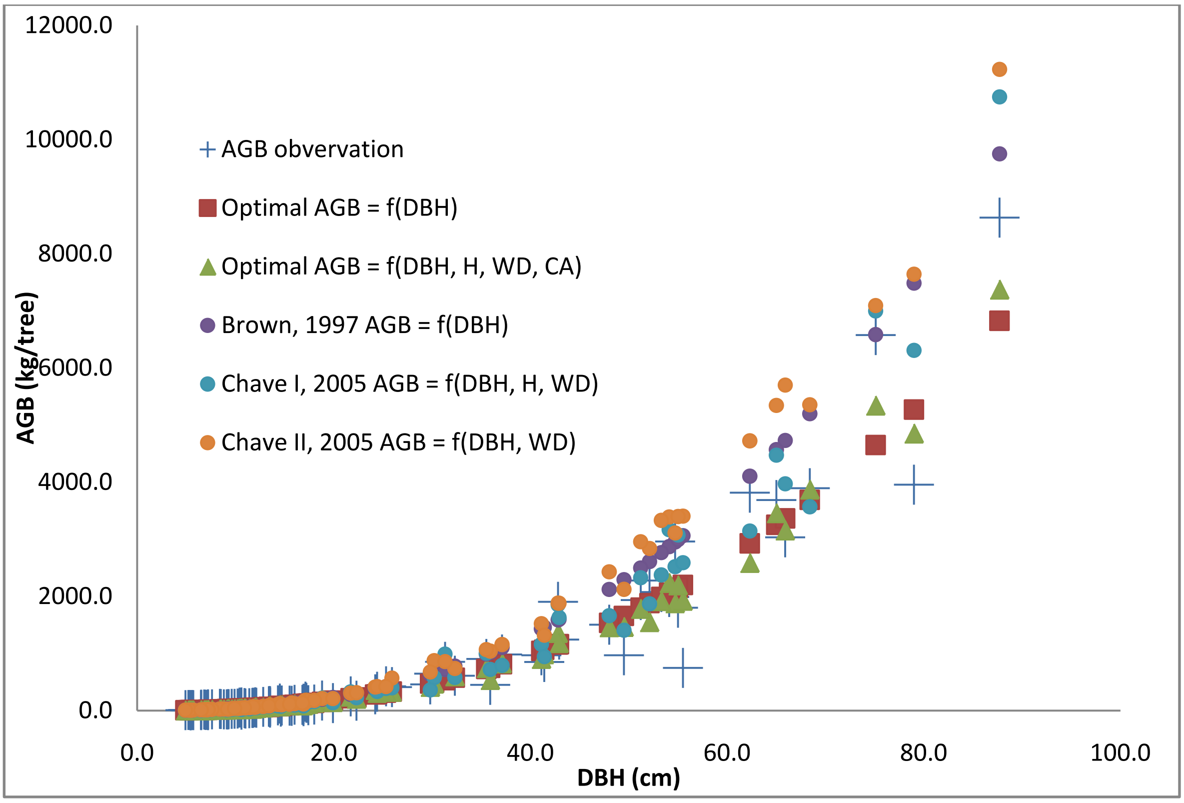


Figure 225: Comparison with pan-tropical equations

Note: Equation 4-4 with DBH as variable “Optimal AGB=f(DBH)”; Equation 4-10 with four variables DBH, H, WD and CA “Optimal AGB=f(DBH, H, WD, CA)”.

According to IPCC (2006), biomass estimates are conducted mainly for AGB, then inferring above ground carbon using a factor of 0.47. The ratio C(AGB)/AGB published by Bao Huy et. al.,(2012)for evergreen broadleaf forests in the Central Highlands of Vietnam where conditions are similar to the study area condition, is 0.468.

Based on the model of AGB estimates, carbon stock and CO_2 can be calculated as follows:

C(AGB) = 0.47*AGB

CO_2 = 3.67* C(AGB)

3.4 BCEF and BEF

3.4.1 BCEF (totalAGB/Vstem)

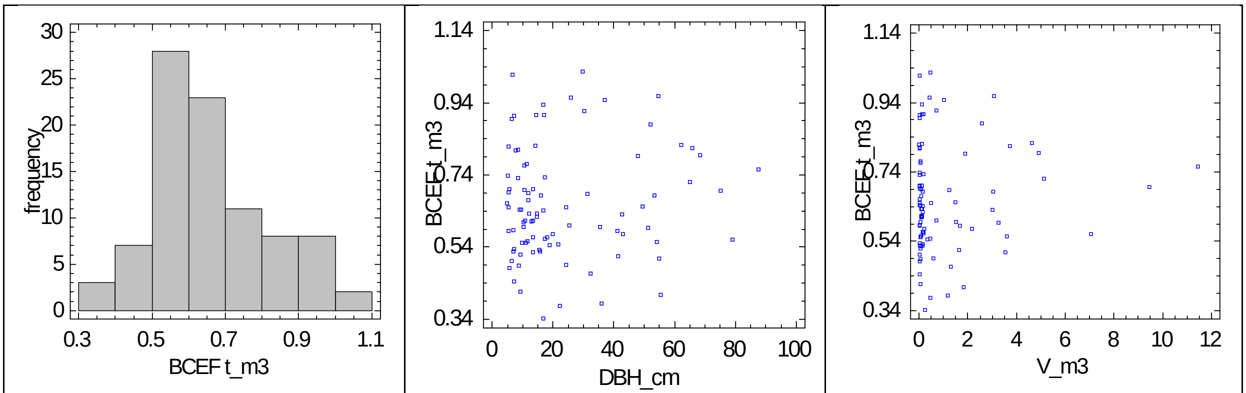
AGB can be estimated through BCEF with the conversion formula: AGB (t) = BCEF* V (m^3). Summary statistic of BCEF (t/m^3) can be calculated (Table 26).

Table 246: Summary Statistics for BCEF (t/m^3)

Count	90
Average	0.657772
Standard deviation	0.153236
Coeff. of variation	23.2962%

Minimum	0.354179
Maximum	1.02614
Range	0.684353
Stnd. skewdness	1.78371
Stnd. kurtosis	-0.51667

The standardized skewdness and also the standardized kurtosis value are within the range expected for data of BCEF of a normal distribution. There is a weak relation observed between BCEF and DBH or V (Figure 26). This means the average BCEF = 0.658 t/m^3 may be applied to convert stand volume (V) to AGB.



BCEF histogram

Graph between BCEF and DBH factor

Graph between BCEF and V factor

Figure 236: BCEF histogram and related to DBH, V

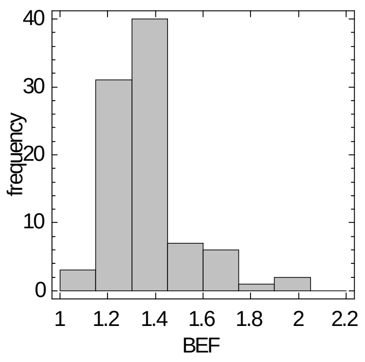
3.4.2 BEF (totalAGB/ABGstem)

AGB can be estimated through BEF with the conversion formula: AGB = BEF*Bst. Summary statistic of BEF can be calculated (Table 27).

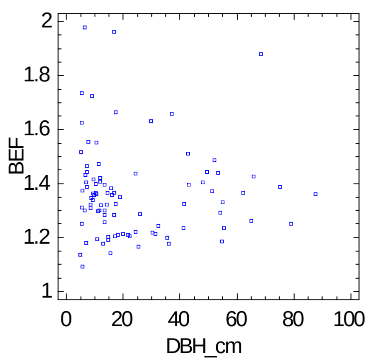
Table 27: Summary Statistics for BCEF (t/m^3)

Count	90
Average	1.36502
Standard deviation	0.170585
Coeff. of variation	12.4969%
Minimum	1.09257
Maximum	1.97751
Range	0.884949
Stnd. skewness	5.84656
Stnd. kurtosis	5.80588

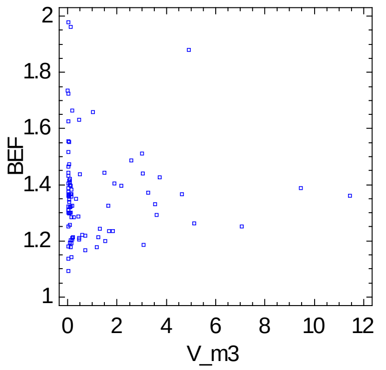
The standardized skewdness and also the standardized kurtosis value are not within the range expected for data of BEF of a normal distribution. There is a weak relation observed between BEF and DBH or V (Figure 27). This means if the average BEF = 1.365 is applied to convert AGB stem (Bst) to total of AGB will be low accuracy.



BEF histogram



Graph between BEF and DBH factor



Graph between BEF and V factor

Figure 27: BEF histogram and related to DBH, V

3.5 Timber volume and AGB in the studied forest type and region

Using the best equations developed in this report and diameter distribution to estimate the average value of volume and AGB in the studied forest type. Results in the table 28 and 29

Table 28: Timber volume and AGB of SP I

Mid. DBH (cm)	*N/ha*	H (m)	V (m3/ha)	AGB (t/ha)
10	803	11.3	41.2	25.9
20	229	17.2	66.5	41.8
30	119	21.3	92.0	58.5
40	58	24.5	88.7	57.2
50	23	27.1	59.4	38.8
60	16	29.4	63.1	41.7
70	8	31.3	45.1	30.1
80	6	33.1	46.0	31.0
90	2	34.6	20.1	13.7
100	1	36.1	12.8	8.8
Tổng	**1265**		**534.7**	**347.4**

Table 29: Timber volume and AGB of SP II

Mid. DBH (cm)	N/ha	H (m)	V (m3/ha)	AGB (t/ha)
10	681	11.3	34.9	22.0
20	231	17.2	67.1	42.1
30	77	21.3	59.5	37.9
40	51	24.5	78.0	50.3
50	20	27.1	51.6	33.7
60	6	29.4	23.7	15.6

70	3	31.3	16.9	11.3
80	4	33.1	30.6	20.7
90	0	34.6	0.0	0.0
100	3	36.1	38.3	26.3
Total	**1076**		**400.6**	**259.8**

4 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

The research objectives were to develop allometric equations for estimate of biomass and carbon stock for evergreen broadleaf forests in the South Central Coastal region of Vietnam. Several key conclusions from the study are as below:

Characteristics of species composition, forest structure, and wood density:

- *Species composition:* Dominant species make up a low ratio of the stand of approximately10%,with total V>50%, the 90% of remaining species IV<2%. This indicates difficulty in sampling to develop separate allometric equations for each species for this forest type in this eco-region.
- *Forest structure:* Low disturbance and high stand volume were found in this stand. The inverted J-shaped distribution by DBH shows the sustainable regeneration trend. BA and M were distributed mainly in the diameter class of 30-40 cm, therefore, to develop allometric equations models, the use of ratio of numbers of trees by BA class well represents the distribution of forest biomass.
- *Wood density (WD)* is an important factor for the estimation of tree and stand biomass. WD is representative for species groups with the same biomass contained in volume unit. The study analyzed WDs of 41 main tree species, varying between 0.430-0.712.

Models of biomass and carbon of the evergreen broadleaf forests for South-Central Coastal Vietnam:

- AGB depends on different plant characteristics, the allometric equation can be developed for each plant family, but this requires enough sample trees while the tropical moist forest contains vast numbers of species and plant families. Development of allometric equations for each plant family can reach higher accuracy, but implies more difficulty in application due to complexity, and possibility of errors in identifying tree species in the field.

The model with one variable of DBH:

$$\mathrm{AGB_{tree}} = \exp(-2.24267 + 2.47464 * \ln(\mathrm{DBH})) \quad \text{Equation 4-4}$$

The model with two variables of DBH and H:

$$\log(AGB_{tree}) = -2.87966 + 2.13303 * \log(DBH) + 0.595399 * \log(H) \quad \text{Equation 4-6}$$

The model with three variables of DBH, H and WD:

$$log(AGB_{tree}) = -2.06535 + 2.14325 * \log(DBH) + 0.543595 * \log(H) + 1.29354 * \log(WD) \quad \text{Equation 4-7}$$

The model with three variables of DBH, H andCA:

$$\log(AGB_{tree}) = -2.88418 + 0.735931 * \log(\mathrm{DBH}^2 * \mathrm{H}) + 0.18307 * \log(\mathrm{DBH}^2 * \mathrm{CA})$$ Equation 4-9

The model with four variables of DBH, H, WD andCA:

$$\log(\mathrm{AGBtree}) = -2.23222 + 0.744261 * \log(\mathrm{DBH}^2 * \mathrm{H}) + 1.13674 * \log(\mathrm{WD}) + 0.17046 * \log(\mathrm{DBH}^2 * \mathrm{CA})$$ Equation 4-10

- The increase of independent variables from one to four reduces deviation of the estimates. All variables of DBH, H, WD and CA affected AGB, of which DBH and H represents the relationship between the tree volume with biomass, while WD and CA well represents the biological characteristics of the species and shape of canopy.
- The model with one factor of DBH can be applied when simplified approaches are necessary, such as in participatory methods of carbon monitoring, as DBH is easily measured by even non-professional actors. In the existing national inventory system, two factors of DBH and H are measured in the plots and used to convert to volume, therefore the model of ABG with two these factors can be applied.
- Adding variables such as WD and CA to DBH and H increases the accuracy of equations. The variable of CA is simple to measure and will not significantly impact surveying costs.
- For evergreen broadleaf forests in the South-Central Coastal region of Vietnam, the models were developed with average deviation of 13-16% comparing to real observations, whereas if the existing models developed generally for tropical forests around the world were applied, the deviation would be higher, (the models of Brown (1997) with S% =43-107%, or Chave (2005) with S% =5-94%, Basuki et al. (2009) for dry dipterocarp forests with S%=26-30%).

4.2 Recommendations

The following are essential recommendations:

1. Applying sampling by ratio of BA, and application of models involving four variables DBH, H, WD and CA is recommended for the specific forest type and eco-region under study.
2. As developed models were validated with independent data, the results of the study should be applied in REDD+.
3. The methods obtained from this study should be applied for all forest types in the specific eco-region in order to develop a comprehensive set of allometric equations for estimating forest carbon country-wide.

REFERENCES

Vietnamese

Võ Đại Hải, 2009. Nghiên cứu khả năng hấp thụ carbon của rừng trồng bạch đàn. Tạp chí NN & PTNT, 1(2009)

Bảo Huy, 2009. Phương pháp nghiên cứu ước tính trữ lượng các bon của rừng tự nhiên làm cơ sở tính toán lượng CO_2 phát thải từ suy thoái và mất rừng ở Việt Nam. Tạp chí Nông nghiệp và Phát triển nông thôn, 1(2009): 85 – 91.

Bảo Huy, 2012. Xây dựng phương pháp giám sát và đo tí nh carbon rừng có s ự tham gia của cộng đồng ở Việt Nam. Tạp chí Rừng và Môi trường, 44 – 45 (2012): 34 – 45.

Bảo Huy, Nguyễn Thị Thanh Hương, Võ Hùng, Cao Thị Lý, Nguyễn Đức Định, (2012): Xác định lượng CO_2 hấp thụ của rừng lá rộng thường xanh vùng Tây Nguyên để tham gia chương trình giảm thiểu phát thải từ suy thoái và mất r ừng. Báo cáo đề tài cấp Bộ trọng điểm. Bộ Giáo Dục và Đào tạo.

Nguyễn Ngọc Lung, 1989. Điều tra rừng thông Pinus kesiya Việt Nam làm cơ sở tổ chức kinh doanh. Luận án Tiến sĩ khoa học. Học viện kỹ thuật lâm nghiệp Leningrad mang tên S.M. Kirov, Leningrad. (Bản dịch tiếng Việt).

Vũ Tấn Phương, 2006. Nghiên cứu trữ lượng carbon thảm tươi và cây bụi: Cơ sở để xác định đường carbon cơ sở trong các dự án trồng rừng/tái trồng rừng theo cơ chế phát triển sạch ở Việt Nam. Tạp chí NN & PTNT.

Ngô Đình Quế, 2007. Khả năng hấp thụ CO_2 của một số loại rừng trồng chủ yếu ở Việt Nam. Viện Khoa học Lâm nghiệp Việt Nam.

English

Bao Huy and Pham Tuan Anh, 2008. Estimating CO_2 sequestration in natural broad-leaved evergreen forests in Vietnam. Asia-Pacific Agroforestry Newsletter, APANews, FAO, SEANAFE, 32(2008): 7 – 10.

Basuki, T.M., Van Lake, P.E., Skidmore, A.K., Hussin, Y.A., 2009. Allometric equations for estimating the above-ground biomass in the tropical lowland Dipterocarp forests. Forest Ecology and Management 257(2009): 1684-1694.

Brown, J. F., Loveland, T. R., Ohlen, D. O., and Zhu, Z. 1999. The global land-cover characteristics database: the user's perspective. Photogrammetric Engineering and Remote Sensing, 65: 1069–1074.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests: a Primer. FAO Forestry paper – 134. ISBN 92-5-103955-0. Available on web site: http://www.fao.org/docrep/W4095E/w4095e00.htm#Contents

Brown, S. 2002. Measuring carbon in forests: current status and future challenges. Environmental Pollution, 3(116): 363–372.

Brown, S. and Iverson, L. R., 1992. Biomass estimates for tropical forests. World Resources Review 4:366-384.

Brown, S., Iverson, L. R., Prasad, A., 2001. Geographical Distribution of Biomass Carbon in Tropical Southeast Asian Forests: A database. University of Illinois.

Brown, S., Gillespie, A.J.R., and Lugo, A.E., 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science 35:881-902.

Brown, S., Sathaye, J., Cannell, M., Kauppi, P., 1996. Management of forests for mitigation of greenhouse gas emissions. In: Watson, R.T., Zinyowera, M.C., Moss, R.H. (Eds.), Climate

Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific- Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, pp. 773–797.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riera, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia145 (2005): 87-99. DOI 10.1007/s00442-005-0100-x.

Chave, J., Condit, R., Aguilar, S., 2004. Error propagation and scaling for tropical forest biomass estimates. Phil. Trans. R. Soc. Lond. B 359(2004): 409–420. DOI 10.1098/rstb.2003.1425

Dietz, J., Kuyah, S., 2011. Guidelines for establishing regional allometric equations for biomass estimation through destructive sampling. World Agroforestry Center (ICRAF).

FCCC, 1997 – 2011: Framework Convention on Climate Change. United Nations.

Henry, H., Besnard, A., Asante, W.A., Eshun, J., Adu-Bredu, S., Valentini, R., Bernoux, M., Saint-Andre, L., 2010. Wood density, phytomass variations within and among trees, and allometric equations in s tropical rainforest of Africa. Forest Ecology and Management Journal, 260(2010): 1375-1388.

Hohenadl,1923. Neue Grundlagen der Holzmessung. Forstw Zentrablatt.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programmed, Eggleston H.S., Buendia L., Miwa K., Ngara T., Tanabe K., (eds). Published: IGES, Japan.

IPCC— 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. IPCC National Greenhouse Gas Inventories Programme, Hayama, Japan. 295 pp.

Johannes, D; Shem, K., 2011, Guidelines for establishing regional allometric equations for biomass estimation through destructive sampling. CIFOR

Ketterings, Q.M., Richard, C., Meine van N., Ambagau, Y., Palm, C.A., 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above ground tree biomass in mixed secondary forests. Forest Ecology and Management 146(2001): 199-209

MacDicken, K.G., 1997. A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects. Winrock International Institute for Agricultural Development.

Mallows, C.L., 1973. Some Comments on CP. Technometrics 15 (4): 661–675. doi:10.2307/1267380. JSTOR1267380.

Pearson, T., R., H., Brown, S., L., Birdsey, R., A., 2007. Measurement Guidelines for the Sequestration of Forest Carbon. United States Department of Agriculture (USDA) Forest Service. General Technical Report NRS-18.

UNFCCC, 1992. United Nation Framework Convention on Climate Change. United Nation.

UN-REDD, 2011. Measurement, Reporting & Verification (MRV) Framework Document. UN-REDD Vietnam Programme.

APPENDICES

Appendix 1: List of tree species within the sample plots

ID	Vietnamese name	Latin name	Family name
1	Xoài	Mangifera flava Evrard.	Anacardiaceae
2	Xây đao	Plaquium gutta (Hook. F.) Baillon	Anacardiaceae
3	Sấu	Sandoricum koetijape (Burm. F.) Merr.	Anacardiaceae
4	Sưng	Semecarpus caudata Pierre.	Anacardiaceae
5	Na lông	Milliulosa bailonii Pierre.	Annonaceae
6	Nhọc lá lớn	Polyalthia laui Merr.	Annonaceae
7	Nhọc	Polyalthia nemoralis A. Dc.	Annonaceae
8	Dền	Xylopia pierrei Hance.	Annonaceae
9	Dền đỏ	Xylopia vielana Pierre ex Fin & Gagn.	Annonaceae
10	Thừng mực	Wrightia laevis Hook. F	Apocynaceae
11	Ngũ gia bì	Scheffera octophylla (Lour.) Harms.	Araliaceae
12	Nút nác	Oroxylum indicum (L.) Vent.	Bignoniaceae
13	Trám trắng	Canarium album (Lour.) Raeusch. Ex DC.	Burseraceae
14	Trám hồng	Canarium bengalensis Guill.	Burseraceae
15	Trám	Canarium littorale Bl.	Burseraceae
16	Trám đen	Canarium tramdenum	Burseraceae
17	Gõ dầu	Sindora tonkinensis A. Chev ex K.S.S Lars	Caesalpiniaceae
18	Lim xẹt	Peltophorum dasirachis (Miq.) Kurz.	Caesalpiniaceae
19	Cám	Parinari annamensis	Chrysobalaceae
20	Vàng nghệ	Garcinia handburyi Hook.F	Clusiaceae
21	Bứa	Garcinia oliveri Pierre.	Clusiaceae
22	Lôi	Crypteronia paniculata Blume var Affinis (Pl.) Beus.	Crypteroniaceae
23	Sổ	Dillenia indica L.	Dilleniaceae
24	Dầu nước	Dipterocarpus alatus Roxb.	Dipterocarpaceae
25	Chò	Shorea farinosa	Dipterocarpaceae
26	Phay bần	Duabanga grandiflora (DC.) Walp.	Dubangaceae
27	Thị lá nhỏ	Diospyros decandra L.	Ebenaceae
28	Thị	Diospyros pilosula Hiern.	Ebenaceae
29	Côm	Elaeocarpus kontumensis Gagn.	Elaeocarpaceea
30	Nhội	Bischofa trifoliata (Roxb.) Hook.	Eurphobiaceae

31	Cù đèn	Croton delpyi Gagnep.	Eurphobiaceae
32	Thầu dầu	Antidesma bunius	Eurphorbiaceae
33	Thầu tấu	Aporosa villosa	Eurphorbiaceae
34	Dâu da	Baccaurea ramiflora Lour.	Eurphorbiaceae
35	Bọt ếch	Glochidion hirsutum (Roxb.) Voigt.	Eurphorbiaceae
36	Mã rạng lá nhỏ	Macaranga kurzii	Eurphorbiaceae
37	Mã rạng	Macaranga tanarius (L.)	Eurphorbiaceae
38	Ba bét	Mallotus paniculatus (Lamk.) Mueli-Arg	Eurphorbiaceae
39	Sòi	Sapium baccatum Roxb.	Eurphorbiaceae
40	Thàn mát	Milletia nigrescens Gagnep.	Fabaceae
41	Dẻ	Lithocarpus annamensis A. Camus.	Fagaceae
42	Sồi	Quescus helferiana A. Dc.	Fagaceae
43	Hồng quang	Rhodoleia championii Hook.F.	Hamamelidaceae
44	Cuống vàng	Gonocaryum lobbianum (Miers) Kurz	Icacinaceae
45	Hồi	Illicium griffithii Hook. F. Thomas.	Illiciaceae
46	Kơ nia	Irvingia malayana Oliv. Ex Benn.	Irvingiaceae
47	Chẹo tía	Engelhardtia spicata var integra (Kurz) Manning	Juglandaceae
48	Quế rừng	CinNamomum curvifolium (Lour.) Nees	Lauraceae
49	Bời lời	Litsea baviensis var venulosa Liouho.	Lauraceae
50	Kháo thơm	Machilus odoratissima Nees.	Lauraceae
51	Kháo	Machilus paviflora Meissn.	Lauraceae
52	Sụ thơm	Phoebe lanceolata (Nees) Nees.	Lauraceae
53	Sụ	Phoebe odoratissima	Lauraceae
54	Vừng	Barringtonia racenmosa (L.) Spreng	Lecythidaceae
55	Bằng lăng ổi	Lagerstroemia calyculata Kurz.	Lithraceae
56	Bằng lăng	Lagerstroemia speciosa (L.) Pers.	Lithraceae
57	Giổi	Magnolia braianensis Gagnep.	Magnoliaceae
58	Ngâu	Aglaia elaeagnoidea Benth.	Meliaceae
59	Gội	Aglaia roxburghiana Miq.	Meliaceae
60	Xoan	Melia azedarach L.	Meliaceae
61	Xoan mộc	Toona surenii (Bl) Merr.	Meliaceae
62	Sóng rắn	Albizia julibrissin Durasz.	Mimosaceae
63	Mít nài	Artocarpus rigida Bl.	Moraceae

64	Máu chó	Knema pierre Warb.	Myristicaceae
65	Mận rừng	Syzygium jambos var sp.	Myrtaceae
66	Trâm trắng	Syzygium levinei Merr. Et Perry.	Myrtaceae
67	Trâm đỏ	Syzygium zeylanicum (L.) Dc.	Myrtaceae
68	Kim giao	Nageia wallichiana (Presl.) O. Ktze.	Podocarpaceae
69	Xoan đào	Prunus ceylanica (Wight.) Miq.	Rosaceae
70	Dành dành	Gardenia philastrei Pierre ex Pit.	Rubiaceae
71	Nhàu	Morinda cochinchinensis Dc.	Rubiaceae
72	Hoắc quang	Wendlandia panicualta (Roxb.) DC.	Rubiaceae
73	Dấu dầu	Euodia lepta (Spreng.) Merr.	Rutaceae
74	Cơm rượu	Glycosmis cyanocarpa	Rutaceae
75	Nhãn rừng	Lepisanthes rubiginosa Leenh..	Sapindaceae
76	Trường chua	Michocarpus paradoxus Radlk.	Sapindaceae
77	Vải rừng	Nephelium hypoleucum Kurz.	Sapindaceae
78	Sến	Madhuca alpina Chev.	Sapotaceae
79	Sp	sp	Sp
80	Lòng máng	Pterospermum diversifolia Bl.	Sterculiaceae
81	Ươi	Scaphium lychnophorum (Hance) Kosterm.	Sterculiaceae
82	Trôm quạt	Sterculia hopochrea Pierre.	Sterculiaceae
83	Trôm	Sterculia parviflora Roxb.	Sterculiaceae
84	An tức hương	Styrax benjoin Dryand.	Styraceae
85	Dung	Symplocos sumuntia Buch.	Symplocaceae
86	Chè rừng	Camelia fleuryi (Pit.) Sealy	Theaceae
87	Huỳnh nương	Ternstroemia japonica Thunb	Theaceae
88	Gió bầu	Aquilaria baillonii Pierre ex Lec.	Thymelaceae
89	Ngát vàng	Gironiera subaequalis Planch.	Ulmaceae
90	Hu đay	Trema orientalis (L.) Bl.	Ulmaceae
91	Bình linh	Vitex plerreana P. Dop.	Verbenaceae

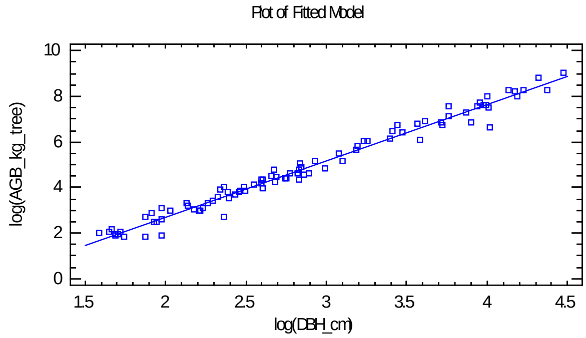
Appendix 2: Average wood density by tree species

Spercies: Viettnamese/Latin name	Meanof WD(g/cm^3)
An Tức Hương	0.557
Styrax benjoin Dryand.	0.557
Bình Linh	0.524
Vitex plerreana P. Dop.	0.524
Bời lời	0.515
Litsea baviensis var venulosa Liouho.	0.515
Bời lời lá bầu dục	0.582
Litsea elliptica	0.582
Bứa	0.627
Garcinia oliveri Pierre.	0.627
Bùi tía	0.581
Ilex annamensis Tard	0.581
Bưởi Bung	0.524
Acronychia oligophlebia Merr	0.524
Chè Rừng	0.597
Camelia fleuryi (Pit.) Sealy	0.597
Chiêu liêu xanh	0.574
Terminalia calamansanai Rolfe.	0.574
Chò	0.611
Shorea farinosa	0.611
Côm	0.584
Elaeocarpus kontumensis Gagn.	0.584
Còng	0.567
Calophyllum dryobalanoides Pierre	0.567
Dành dành	0.566
Gardenia philastrei Pierre ex Pit.	0.566
Dâu da	0.603
Baccaurea ramiflora Lour.	0.603
Dẻ	0.580
Lithocarpus annamensis A. Camus.	0.580
Gáo	0.430

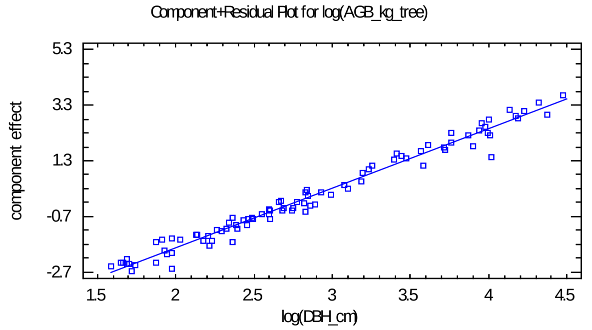
Nauclea orientalis L.	0.430
Giổi	0.599
Magnolia braianensis Gagnep.	0.599
Gội	0.583
Aglaia roxburghiana Miq.	0.583
Lộc vừng	0.531
Barringtonia racenmosa (L.) Spreng	0.531
Lòng Máng Lá Nhỏ	0.556
Pterospermum diversifolia Bl.	0.556
Máu chó	0.598
Knema pierre Warb.	0.598
Ngát	0.526
Gironiera subaequalis Planch.	0.526
Ngâu rừng	0.485
Aglaia elaeagnoidea Benth.	0.485
Nhãn Rừng	0.605
Lepisanthes rubiginosa Leenh..	0.605
Nhọc	0.591
Polyalthia nemoralis A. Dc.	0.591
Re Hương	0.626
Cinnamomum subavenium Miq.	0.626
Săng máu	0.565
Hosfieldia amygdalina (Wall.) Warb.	0.565
Sến	0.631
Madhuca alpina Chev.	0.631
Sổ	0.531
Dillenia indica L.	0.531
Sòi	0.560
Sapium baccatum Roxb.	0.560
Sơn huyết	0.626
Melanorhea laccifera Pierre.	0.626
Thị	0.624
Diospyros pilosula Hiern.	0.624

Thị rừng	0.664
Diospyros decandra	0.664
Trám	0.626
Canarium littorale Bl.	0.626
Trâm	0.596
Syzygium levinei Merr. Et Perry.	0.596
Trôm	0.589
Sterculia parviflora Roxb.	0.589
Ươi	0.594
Scaphium lychnophorum (Hance) Kosterm.	0.594
Vàng nghệ	0.694
Garcinia handburyi Hook.F	0.694
Vạng trứng	0.570
Endospermum sinensis Benth.	0.570
Xoan	0.502
Melia azedarach L.	0.502
Xoan đào	0.589
Prunus ceylanica (Wight.) Miq.	0.589

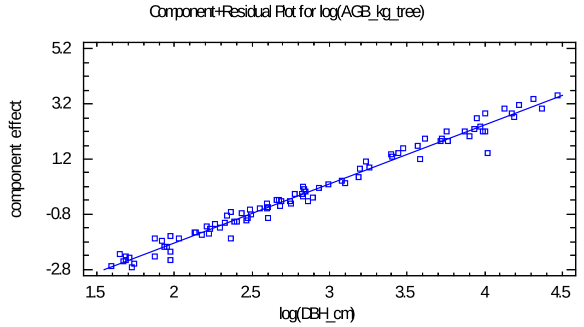
Appendix 3: Figures presenting correlation of AGB with variables DBH, H, WD, CA and V based on optimal models selected in this study



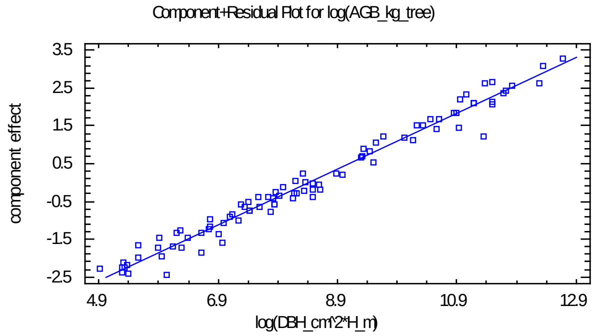
$\log(AGB_{tree}) = -2.24267 + 2.47464*\ln(DBH)$



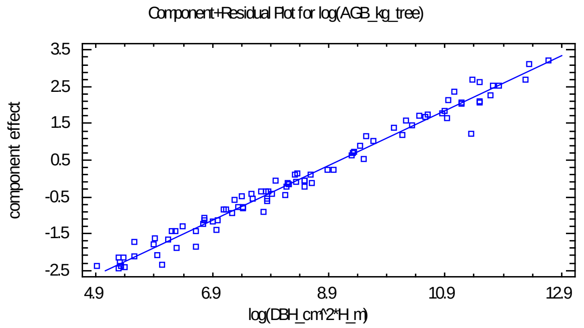
$\log(AGB_{tree}) = -2.87966 + 2.13303*\log(DBH) + 0.595399*\log(H)$



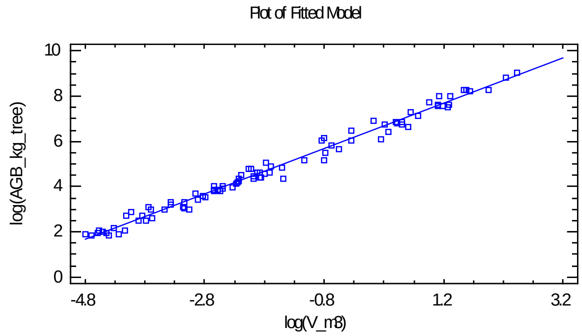
$\log(AGB_{tree}) = -2.06535 + 2.14325*\log(DBH) + 0.543595*\log(H) + 1.29354*\log(WD)$



$\log(AGB_{tree}) = -2.88418 + 0.735931*\log(DBH^2*H) + 0.18307*\log(DBH^2*CA)$

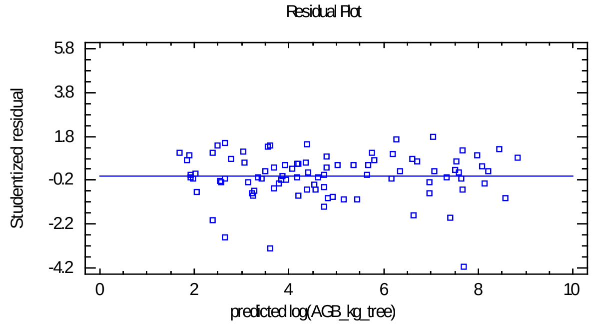


$\log(AGB_{tree}) = -2.23222 + 0.744261*\log(DBH^2*H) + 1.13674*\log(WD) + 0.17046*\log(DBH^2*CA)$

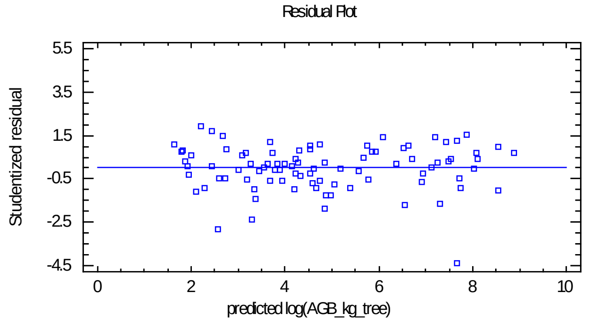


$\log(AGB_{tree}) = 6.46499 + 1.00179*\log(V)$

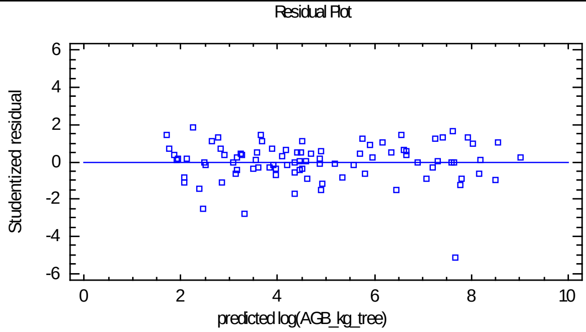
Appendix 4: Figures presenting residuals against predictions based on models selected in this study



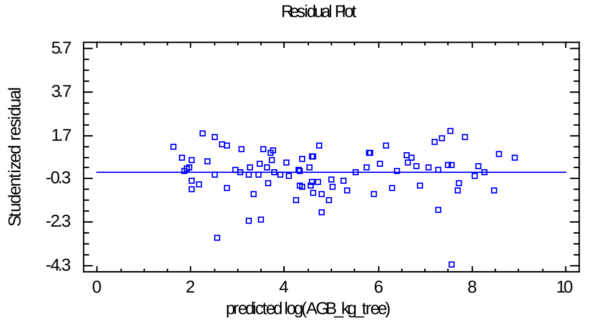
$\log(AGB_{tree}) = -2.24267 + 2.47464 * \ln(DBH)$



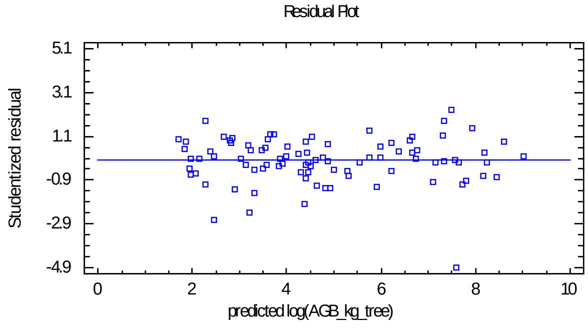
$\log(AGB_{tree}) = -2.87966 + 2.13303 * \log(DBH) + 0.595399 * \log(H)$



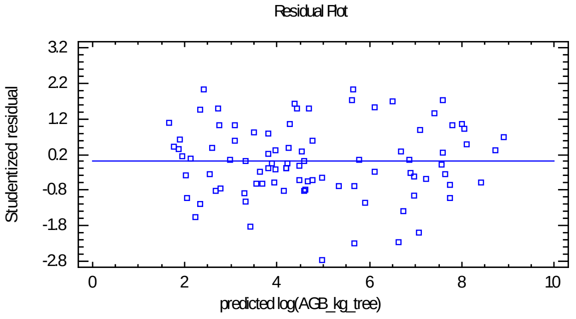
$\log(AGB_{tree}) = -2.06535 + 2.14325 * \log(DBH) + 0.543595 * \log(H) + 1.29354 * \log(WD)$



$\log(AGB_{tree}) = -2.88418 + 0.735931 * \log(DBH^2 * H) + 0.18307 * \log(DBH^2 * CA)$

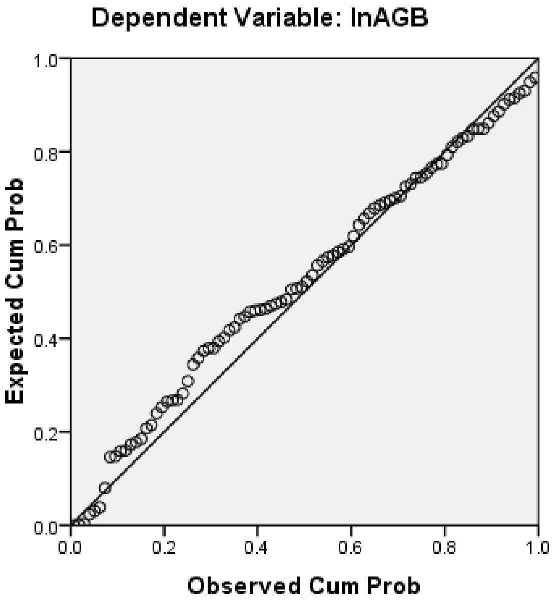


$\log(AGB_{tree}) = -2.23222 + 0.744261 * \log(DBH^2 * H) + 1.13674 * \log(WD) + 0.17046 * \log(DBH^2 * CA)$

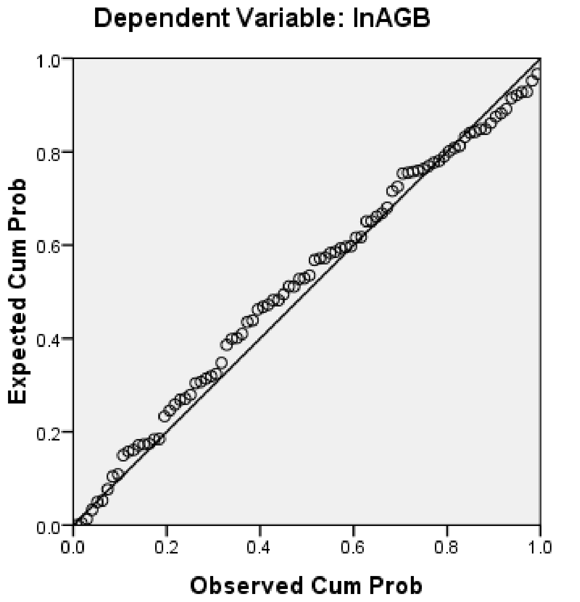


$\log(AGB_{tree}) = 6.46499 + 1.00179 * \log(V)$

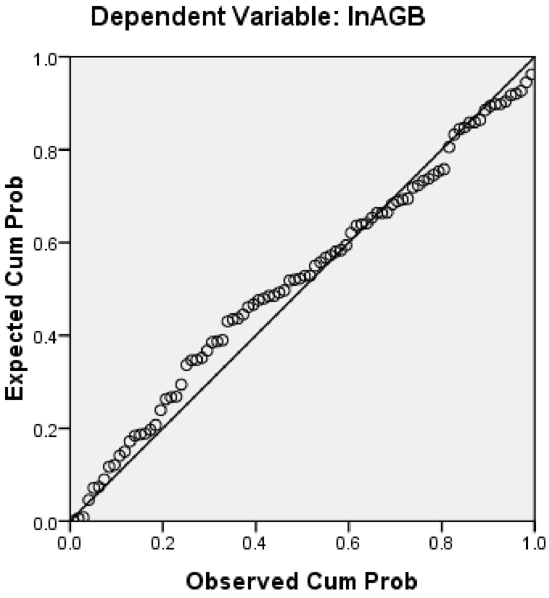
Appendix 5: Figures presenting normal P-P plot of regression standardized residual of models selected in this study

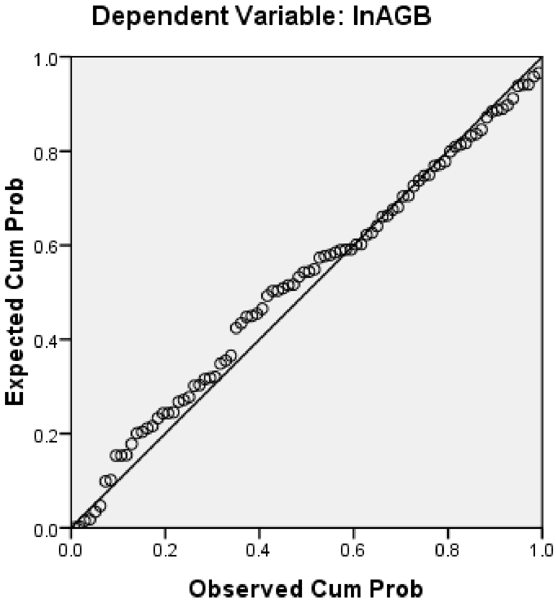


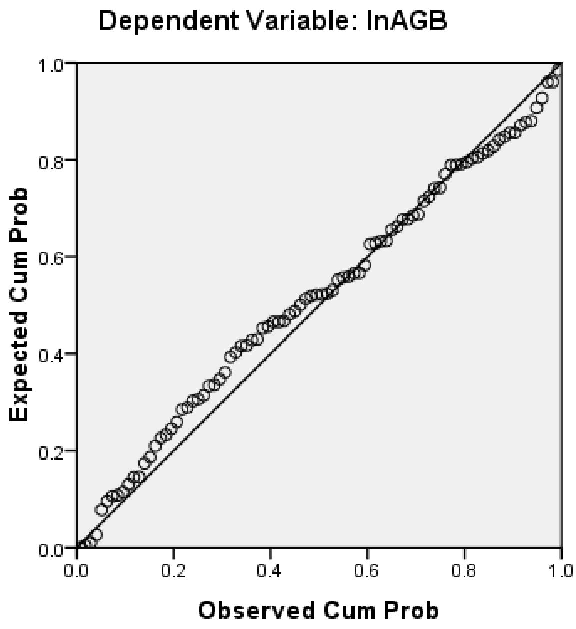
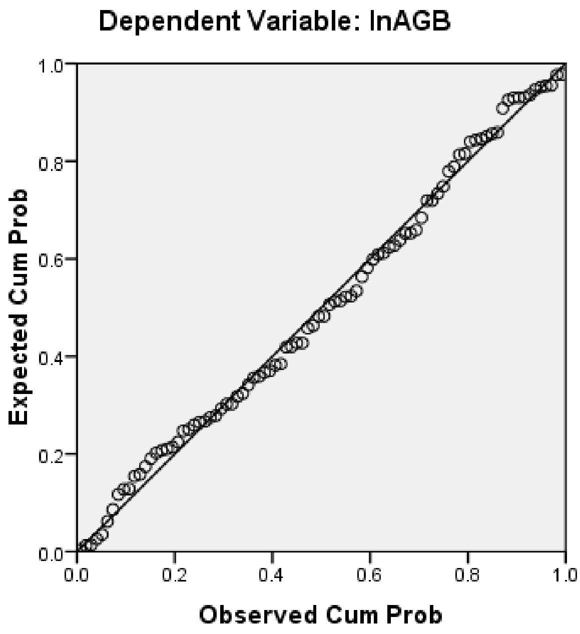
$\log(AGB_{tree}) = -2.24267 + 2.47464 * \ln(DBH)$



$\log(AGB_{tree}) = -2.87966 + 2.13303 * \log(DBH) + 0.595399 * \log(H)$





<table>
<tr>
<td>$\log(AGB_{tree}) = -2.06535 + 2.14325*\log(DBH) + 0.543595*\log(H) + 1.29354*\log(WD)$</td>
<td>$\log(AGB_{tree}) = -2.88418 + 0.735931*\log(DBH^2*H) + 0.18307*\log(DBH^2*CA)$</td>
</tr>
<tr>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>$\log(AGB_{tree}) = -2.23222 + 0.744261*\log(DBH^2*H) + 1.13674*\log(WD) + 0.17046*\log(DBH^2*CA)$</td>
<td>$\log(AGB_{tree}) = 6.46499 + 1.00179*\log(V)$</td>
</tr>
</table>