



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

Βу

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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.

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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(V) = -9.68839 + 0.956145 * log(DBH² * H)

(log: Logarit neper)

The selected models for AGB estimation with DBH only:

 $AGB_{tree} = exp[2 - 2.24267 + 2.47464 * ln(DBH)]$

and the one with the best accuracy:

log(AGBtree) = -2.23222 + 0.744261 * log(DBH² * H)+ 1.13674 * log(WD) + 0.17046 * log(DBH² * CA)

The average BCEF = 0.658 t/m^3 with 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: $400.6 - 534.7 \text{ m}^3$ /ha and the total AGB per ha: 259.8 - 347.4 ton/ha.

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LIST OF ACRONYMS

| Α | Age, year |
|--------------------------|--|
| AGB | Above ground biomass (kg/tree) |
| AGBf | Fresh Above ground biomass (kg/tree) |
| BA | Basal area (m²/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) |
| BI | 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 |
| СОР | 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) |
| М | Stand volume(m³/ha) |
| Ν | 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 (m³/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 "IIIA₃": 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:
 - o 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
 - o 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)

| | S of the study sites | |
|-------------|---------------------------|---------------|
| Coordinates | SPI | SPII |
| Latitude | 15 ⁰ 28'13.3'' | 15°28'16.1'' |
| Longitude | 107°48'59.6'' | 107°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 |
| | Bse ⊪ □ | |

Table 1: Geographic coordinates of the study sites

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

2.2 Study site characteristic¹

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°C; the hottest temperature is 39.4°C, while the coldest is 16°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).

| DBH class (cm) | #of stan in the sa | ding trees mple plot | # of felled modeling | trees for # of felled training # and the second sec | | trees for | Total # of trees cut for | Total #of trees cut for | |
|----------------------|-----------------------|-------------------------|-------------------------|--|------|-----------|--------------------------------|-------------------------------|--|
| | SP I | SP II | SP I | SP II | SP I | SP II | modeling | validation | |
| 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 2: Sampled trees

| | | Number of |
|----|------------------|--------------|
| Id | Family name | 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 |

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

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 Cutting branches segments

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 D₀₀, D₀₁, D₀₂, D₀₃, D₀₄ respectively.)



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

calculated as:

7



0.01g was used to weigh the samples.

Leaf samples

I31 I31 001 D02 57

Sample for WD determination

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.

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

Bfst = Bfst + ba - BfbaEquation 3-3 Preparing samples of four tree components for biomass and wood density calculation:

segments of the stem.

Fresh biomass of stem (Bfst) was determined as:

 $Bfba = dfba * Vba. 10^3$

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

dba = m/VbaEquation 3-1

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

To separate the bark from the stem, at position of one fifth length fresh bark samples were taken

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.

and weighed (m) with accuracy of 0.1 mg. 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 (cm³).

Weighing fresh biomass of tree components:

Weighing leaves Weighing stem and bark Weighing branches Figure 5: Images of weighing fresh biomass of sample tree components





Equation 3-2







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°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 (cm³). Dry biomass (m) of each sample was defined as dry oven temperature of 105° 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

Equation 3-4





Preparation of samples for calculating dry biomass and analysis of carbon



Oven drying at 105°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):

$$IV = (N + BA)/2$$
 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):

$$V = \frac{L \cdot \pi \cdot 10^{-4}}{80} \{ (Doo + D01)^2 + (Do1 + D02)^2 + (Do2 + D03)^2 + (Do3 + D04)^2 + (D04)^2 \}$$
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:

$$CA = \pi . CD^2/4$$
 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:

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

Biomass Conversion and Expansion Factor (BCEF) (t/m³) (IPCC, 2003)

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

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

$$BEF = AGB/Bst$$
 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) 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 (R²):* Generally, the highest R² value with statistical significance level exhibits the optimal model. However, in some cases, despite the R² 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(RSE²/2), 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.

³Data 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.

$$AIC = n * \ln\left(\frac{RSS}{n}\right) + 2K = -\ln(L) + 2K$$
 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%):

$$S\% = \frac{100}{n} \sum_{i=1}^{n} \frac{|\operatorname{Yilt} - \operatorname{Yi}|}{\operatorname{Yi}}$$
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 multiplevariable but linearized: four statistical indicators R²,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 | 0.9897 | 97.94% |
| log(Y) = a + b*log(X) | | |
| Square root-Y | 0.9774 | 95.53% |
| $Sqrt(Y) = a + b^*X$ | | |
| Logarithmic-Y square root-X | 0.9749 | 95.04% |
| log(Y) = a + b*sqrt(X) | | |
| Square root-Y squared-X | 0.9665 | 93.41% |
| $sqrt(Y) = a + b^*X^2$ | | |
| Squared-X | 0.9531 | 90.84% |
| $Y = a + b^* X^2$ | | |
| Double square root | 0.9511 | 90.47% |
| <pre>sqrt(Y) = a +b*sqrt(X)</pre> | | |
| Exponential | 0.9350 | 87.42% |
| $log(Y) = a + b^*X$ | | |
| S-curve model | -0.9240 | 85.38% |
| log(Y) = a + b/X | | |
| Double reciprocal | 0.9013 | 81.24% |
| 1/Y = a + b/X | | |
| Square root-Y logarithmic-X | 0.8958 | 80.25% |

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

- 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 R² 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 R² 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).

| Id | Vietnamese name | Scientific name | BA (m²) | 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 |

3.1.1.1.1.1 Table 4: Ratio of dominant species in study site

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 (m²/ha) | M (m³/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 (m²/ha) | M (m³/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 \ge 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 m²/ha and M from 400to 535 m³/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).

| 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:

$$H = (0.702606 + 1.15182 * \log(DBH))^2$$
 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 (cm³). 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, m³) with DBH (cm) only in two models were tested (Table 10).

| | | | | - , | | | | |
|---|-----------------------------------|-------|----|-------|-------|----------|------------------|------------------|
| Equations | R ² adjusted (%) | Ρ | 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% |

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

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

log(V) = a + blog(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).

| Equations | R ² adjusted (%) | Р | 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 |

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

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

 $log(V) = a + blog(DBH^{2}H) \text{ or } V = c(DBH^{2}H)^{b}:$ $log(V) = -9.68839 + 0.956145 * log(DBH^{2} * H)$ 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.





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 DBH²*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 for each component will result in high uncertainty.

| | R ² adjusted (%) | Р | 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 |

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

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





Figure 156: Fitted model of biomass of 4 components with variable DBH² 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.

| 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 |

Table 123: Descriptive statistics of variables

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).

| 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 |

Table 134: Normalization of variables

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 | 0.9897 | 97.94% |
| log(Y) = a + b*log(X) | | |
| Square root-Y | 0.9774 | 95.53% |
| Sqrt(Y) = a + b*X | | |
| Logarithmic-Y square root-X | 0.9749 | 95.04% |
| log(Y) = a + b*sqrt(X) | | |
| Square root-Y squared-X | 0.9665 | 93.41% |
| sqrt(Y) = a +b*X^2 | | |
| Squared-X | 0.9531 | 90.83% |
| Y = a +b*X^2 | | |
| Double square root | 0.9511 | 90.46% |
| sqrt(Y) = a +b*sqrt(X) | | |
| Exponential | 0.935 | 87.42% |
| $log(Y) = a + b^*X$ | | |
| S-curve model | -0.924 | 85.38% |
| log(Y) = a + b/X | | |
| Double reciprocal | 0.9013 | 81.23% |
| 1/Y = a + b/X | | |
| 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 o | f AGB with | independent | variable of DBH |
|------------|-------------|------------|-------------|-----------------|
| 1000 | | | maoponaom | |

| | | op 0 | | | | | | |
|---|-----------------------------------|-------|----|-------|----------|----------|------------------|------------------|
| Equation | R ² adjusted (%) | Ρ | 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:



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 =
$$exp(-2.134 + 2.530 * ln(DBH))$$
 Equation 4-5

DBH=5-148cm, n=170 trees, R²=0.970

| Table 107. Comparison of Drown (1997) with selected equation for DBT | | | | | | |
|--|------------------|------------------|--|--|--|--|
| | S ₁ % | S ₂ % | | | | |
| Brown (1997) | 39.9 | 39.9 | | | | |
| Equation 4-4 | 23.0 | 15.1 | | | | |

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

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).

| Equation | R ² adjusted (%) | Ρ | n | Pi | CF | AIC | S ₁ % | S₂% |
|---|-----------------------------------|-------|----|-------|-------|----------|------------------|------|
| 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 |

Table 178: Models of AGB estimate by DBH and H

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:



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).

| Equation | R ² adjusted (%) | Р | 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*W D) | 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:

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

| 1 | , 1 | • |
|---------------------------|------------------|------------------|
| | S ₁ % | S ₂ % |
| Equation 4-8 Chave (2005) | 23.6 | 22.7 |
| Equation 4-7 | 18.3 | 13.5 |

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

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).

| | Sumate by D | Dri, rran | u OA | | | | | |
|---|-----------------------------------|-----------|------|-------|-------|----------|------------------|------------------|
| Models | R ² adjusted (%) | Ρ | 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 |

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

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.

 $log(AGB_{tree}) = -2.88418 + 0.735931 * log(DBH² * H) + 0.18307$ * log(DBH² * 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 adjust ed (%) | Ρ | 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(AGBtree) = -2.23222 + 0.744261 * log(DBH² * H)+ 1.13674 * log(WD) + 0.17046 * log(DBH² * 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 measured commercial 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 (R²) to determine selection of equation.

Multiplicative and Linear were selected (Table 24).

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/XSquare root-Y 0.9455 89.39% Sqrt(Y) = a + b*XSquare 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)0.8961 80.30% Square root-Y logarithmic-X 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*XSquare 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/XSquared-Y logarithmic-X 0.4859 23.61% $Y^2 = a * b*log(X)$ Reciprocal-X 11.05% -0.3324 Y = a + b/XSquared-Y reciprocal-X 3.50% -0.1872 $Y^2 = a + b/X$

Table 224: Comparison of Alternative Models of AGB and V

Table 235: Equations of AGB by V

| | | R ² adjusted (%) | Р | 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 $AGB = c*V^b$:

$$log(AGBtree) = 6.46499 + 1.00179 * log(V)$$
 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)"):

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

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

$$AGB_{tree} = exp(-2.977 + log(WD * DBH2 * H))$$
 Equation 4-52

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

$$AGB_{tree} = WD * exp(-1.499 + 2.148 * log(DBH) + 0.207 * (log(DBH))^2 - 0.0281 * (log(DBH))^3)$$
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 CO₂ 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).

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

| Table 246: | Summary | Statistics [•] | for | BCEF | (t/m^3) | 'n) |
|-------------|-----------|-------------------------|-----|------|-----------|-----|
| 10010 - 101 | Carrinary | oranouoo | | | (| , |

| 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.



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).

| 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.



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

| 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 28: Timber volume and AGB of SP I

| Table 29: Timber | volume and AGB of SP | Ш |
|------------------|----------------------|---|
|------------------|----------------------|---|

| 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 |

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

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:

$$AGB_{tree} = exp(2-2.24267 + 2.47464 * ln(DBH))$$
 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) 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) Equation 4-7

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

$$log(AGB_{tree}) = -2.88418 + 0.735931 * log(DBH2 * H) + 0.18307$$

* log(DBH² * CA) Equation 4-9

The model with four variables of DBH, H, WD and CA:

$$log(AGBtree) = -2.23222 + 0.744261 * log(DBH2 * H) + 1.13674 * log(WD) + 0.17046 * log(DBH2 * CA) Equation 4-10$$

- 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:

- 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.

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APPENDICES

| 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 xệt | Peltophorum dasirachis (Miq.) Kurz. | Caesalpiniaceae |
| 19 | Cám | Parinari annamensis | Chrysobalaceae |
| 20 | Vàng ngh <mark>ệ</mark> | 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 |

Appendix 1: List of tree species within the sample plots

| 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 BI. | 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 |
| | | | |

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



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



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

