UN-REDD PROGRAMME

PART B-2: Tree allometric equations in Evergreen broadleaf and Bamboo forests in the North East 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 and Bamboo forests in the North East region

By

Nguyen Dinh Hung, Division of Sciences, Techniques and Technologies

Le Truong Giang, Dao Ngoc Tu, Pham Tran Hung, Pham Thanh Lam, Nguyen Tien Khanh, Ha Manh Thuy, the North West Sub Forest Inventory and Planning Íntitute

Forest Inventory and Planning Institute

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

Recommended citation: Hung, N.D., Giang, L.T., Tu, D.N., Hung, P.T., Lam, P.T., Khanh, N.T., Thuy, H.M. (2012) Tree allometric equations in Evergreen broadleaf and Bamboo forests in the North East 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.

ACKNOWLEDGEMENTS

The authors would like to thank the Director and staff members of Bac Kan Forestry Co., Ltd, Department of Agriculture and Rural Development of Bac Kan province, Forestry Department of Bac Kan Province, for their professional advice, help and co-operation in the implementation process of this project.

We would also like to acknowledge Dr. L. Saint-André (CIRAD-INRA) and Dr. M. Henry (FAO) for their useful lectures and teaching materials from the workshop on development of allometric equation for biomass estimation.

We are very grateful to Mrs. Akiko Inoguchi (FAO-VN) and Dr. Pham Manh Cuong (VN-FOREST and VRO) for their frequent advice and regular supervision on our project.

Finally, we would like to thank the Food and Agriculture Organization of the United Nations (FAO), UN-REDD Vietnam Programme for funding and paving a convenient way for this project.

EXECUTIVE SUMMARY

This report describes the process of developing biomass allometric equations and biomass conversion and expansion factors for biomass estimation of the evergreen broadleaved and bamboo forests in the North East Region of Vietnam. Destructive sampling was done to collect biomass data of sample trees and use these data as dependent variables in the multiple regression analysis. Equations from various different statistical models and regression approaches were developed and compared. For equations that developed using the least squares approach, the adjusted R^2 was used for comparison. For equations developed using the maximum likelihood approach, the AICc was used as for comparison. Cross validation tests were conducted to assess the errors of prediction and compare the equations across different regression approaches. For woody forests, the best chosen AEs were compared with previously published AEs, including those of Basuki *et al.* (2009), Brown (1997) and Chave *et al.* (2005).

For evergreen broadleaf forest, analyzed results of 9 statistical models using three regression approaches have lead to the recommendation of using the following four equations, which are the best for each group of input variables:

Equation[1]	Expected value of error[2] (%)	Range of error[3] (95% CL)
$AGB = 0.1142×D^{2.4451}$	1.2603	-11.85 ÷ 15.55
$AGB = 0.0547×D^{2.1148}×H^{0.6131}$	-0.5614	-13.08 ÷ 13.21
$AGB = 0.2176×D^{2.3825}×ρ^{0.7996}$	1.0463	-8.17 ÷ 11.46
$AGB = 0.1173×(D^2H^{0.7}ρ)^{0.9898}$	-0.3002	-8.14 ÷ 8.24

[1] AGB is the above-ground biomass in kg; D is the diameter at breast height in cm; H is the height in m; and ρ is the wood density in g/cm^3 of the tree.

[2] The error here means the error (in percentage) of the predicted total AGB as compared to the measured total AGB of a set of trees.

[3] These ranges of error apply when predicting the total AGB for datasets of 72 or more trees. For datasets with smaller number of trees, the ranges of error may be larger.

The results also indicated that the inclusion of height and wood density as additional input variables contributes to the improvement of prediction. Therefore, whenever these variables are available, the equations that use them should be applied. Moreover, the inclusion of wood density improves the robustness of prediction much more than the inclusion of height so wood density should be given the first priority when considering additional variables. The comparison with previously published AEs has shown that all three previously published AEs tend to over-estimate the total AGB of the trees in the studied dataset. The total AGB errors of the Basuki *et al.* (2009), Brown (1997) and Chave *et al*. (2005) AEs for the current dataset are 3.49%, 44.75% and 25.55%, respectively. These results imply that countries need to develop their own specific AEs in order to improve the certainty of biomass prediction and carbon stock assessment.

An attempt was also made to estimate BEF for evergreen broadleaf forests. The results show that BEF do not depend on DBH but vary around a constant, which is 1.238 for BEF.

For *Indosasa angustata* bamboo forest, analyzed results of four statistical models using three regression approaches have lead to the recommendation of using the following AE:

Equation	Expected value of error (%)	Range of error[1] (95% CL)
$AGB = 0.2184 \times D^{1.8517}$	-0.031	-12.59 ÷ 14.28

[1]These ranges of error apply when predicting the total AGB for datasets of 23 or more trees. For datasets with smaller number of trees, the ranges of error may be larger.

The analyzed results also show that the inclusion of variable H does not improve the accuracy nor the robustness of the prediction. Equations developed specifically for each age class improve the robustness but degrade the accuracy of the prediction. Therefore, for *Indosasa angustata* forest, it is recommended not to include H and age class as input variables for biomass prediction.

For *B. chirostachyoides* bamboo forests, analyzed results recommend the use of the following two equations:

Equation	Expected value of error (%)	Range of error[1] (95% CL)
$AGB = 0.5043 \times D^{1.4587}$	-0.096	-4.34% ÷ 4.28%
$AGB = 0.3153 \times D^{1.3450} \times H^{0.2528}$	-0.229	-3.78% ÷ 3.43%

[1]These ranges of error apply when predicting the total AGB for datasets of 40 or more trees. For datasets with smaller number of trees, the ranges of error may be larger.

The results show that the inclusion of H only slightly improves the robustness (but with the price of slightly reducing the accuracy) of the prediction. Because heights of standing bamboos are quite difficult to measure accurately, it is recommended that for bamboo forests, it is not necessary to include the variable H in biomass prediction.

Age-class specific AEs were also developed for *B. chirostachyoides* forest. The analyzed results show that age class specific AEs does not improve the robustness nor the accuracy of biomass prediction. Thus, it is suggested not to include the age class variable in biomass prediction for *B. chirostachyoides* forest.

In order to improve the certainty of biomass prediction in the studied region, the next studies should concentrate on the development of AEs and BCEFs specified to each tree family or wood density class. Since the range of error of the best model for *Indosasa angustata* forests is still quite large (> ±10%), destructive sampling of more sample trees for *Indosasa angustata* forests is also recommended.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABBREVIATION AND ACRONYMS

AD	Activity Data
AFOLU	Agriculture, Forestry and Other Land Use
AGB	Above-Ground Biomass
AIC	Akaike Information Criterion
AICc	Akaike Information Criterion with correction
BCEF	Biomass Conversion and Expansion Factor
BEF	Biomass Expansion Factor
BGB	Below-Ground Biomass
CL	Confidence Limits
CFIC	Centre for Forest Information and Consultancy
COP	Conference of the Parties
CV	Coefficient of Variation
DBH	Diameter at Breast Height
EF	Emission Factors
FAO	Food and Agriculture Organization of the United Nations
FIPI	Forest Inventory and Planning Institute
FSIV	Forest Science Institute of Vietnam
GHG-I	Green House Gas -Inventory
IPCC	Inter-governmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
MRV	Measurement, Reporting and Verification
QA/QC	Quality Assessment/Quality Control
SSE	Sum of Squared Errors
TNU	Tay Nguyen University
UNFCCC	United Nations Framework Convention on Climate Change
UN-REDD	United Nations Collaborative Program on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
VFU	Vietnam Forestry University
VRO	Vietnam REDD Office
WD	Wood Density
IV(%)	Importance Value

1 INTRODUCTION

In order to prepare for implementing REDD+ in Vietnam, the UN-REDD Vietnam Programme has supported four forestry-related institutions, namely, Forest Science Institute of Vietnam (FSIV), Forest Inventory and Planning Institute (FIPI), Vietnam Forestry University (VFU) and Tay Nguyen University (TNU) to carry out a Study on Development of Allometric Equations for Forest Biomass Estimation. The objective of this Study is to develop a scientific base for forest biomass estimation, including allometric equations (AEs) and biomass conversion and expansion factors (BCEFs), for major natural forests types in Vietnam contributing to MRV under REDD+ and to compilation of the national GHG inventory in the land use, land use change and forestry sector. Destructive sampling has been chosen to develop the AEs and BCEFs.

The Study is implemented in two phases. The initial phase was carried out in 2011. The objectives include reviewing literature relating to biomass estimation, developing a Guidelines on Destructive Measurement for Forest Biomass Estimation (UN-REDD Vietnam and FAO 2012), and testing the Guidelines by carrying out destructive measurement on four pilot plots (two evergreen broadleaved forest plots and two bamboo forest plots). FIPI has carried out destructive measurement on two pilot plots (one evergreen broadleaved forest and one bamboo forest) in Lao Cai province of the North East region. VFU has carried out destructive measurement in two other pilot plots in Nghe An and Thanh Hoa provinces of the North Central Region.

The second phase is carrying out in 2012. One of the activities of this phase is to conduct forest biomass field measurements for selected forest types in 8 selected provinces. The North West Sub FIPI has been assigned to conduct destructive measurement on three evergreen broadleaved forest plots (one in Lao Cai province, two in Bac Kan province of the North East Region), and one bamboo forest plot in Bac Kan province.

Furthermore, the North West Sub FIPI has been assigned to carry out development of allometric equations for biomass estimation in the North East Region using data of its allocated plots together with data of two pilot plots in Lao Cai province of the initial phase. The collected data are used for regression analysis, using different variables, to develop allometric equations for estimation of forest biomass. The North West Sub FIPI is also responsible for carrying out error assessment for their developed AEs using the independent data from sample trees collected for error assessment.

This report describes the implementation process and results of the second phase of the Study conducted by the North West Sub FIPI. The report is organized as follows: Section 2 describes materials and methods used in the Study. Section 3 gives a description of the surveyed areas. Section 4 presents the results together with discussion of these findings. Finally, conclusions and recommendations are provided in Section 5.

2 MATERIALS AND METHODS

The field measurement of forest biomass were conducted through sample plots following the draft version of the Guidelines on Destructive Measurement for Forest Biomass Estimation developed (UN-REDD Vietnam 2012).

2.1 Sampling strategy

2.1.1 Location and design of the plots

Evergreen Boradlevead forest

The establishment of sample plots were conducted to meet the following criteria: i) representativeness (based on assessment of experts) of the forest types being studied; ii) representativeness for topographic conditions; and iii) covering a number of different tree sizes; iv) the sample plots should be set up on less disturbed forests where large sized trees are available (preferably in rich forests, and as a minimum in medium (quality) forests[1]).

The area of each sample plot is 1 ha. The plot is a square of 100 m x 100 m. In steep areas (slope gradient larger than 20°), four sub-sample plots of 0.25 ha (50 m x 50 m) each were used instead.

All live trees with DBH from 5 cm and above in the sample plots were measured. The information collected include: i) tree species (Vietnamese and scientific names); and ii) DBH of trees.

The information of the three sample plots and their location on satellite image is given below.

Table 1: Description of the sample plot LC-VB-01

Plot name	LC-VB-01
Administrative location	Sub-compartment 2, Compartment 517, Lũng Nặm village, Liem Phu commune, Van Ban district, Lao Cai province
Coordinate (VN2000 projection)	Lat = 21°57’30” N; Long = 104°19’50” E;
Altitude	750 m
Slope	30°
Plot area	1 ha
Plot size	100 x 100 (m)
Forest type	Evergreen broadleaved forest (forest with ≥ 75% of broadleaf tree species and green all around the year)
Forest status	IIIA3 (forest that has been slightly affected; the structure is almost unchanged)
Volume (estimated)	290 m^3/ha

[1] According to Circular 34/TT-BNN issued by MARD, a rich forest is a forest with a standing wood volume of 201 – 300 m^3/ha and that of medium forest is 101 – 200m^3/ha.

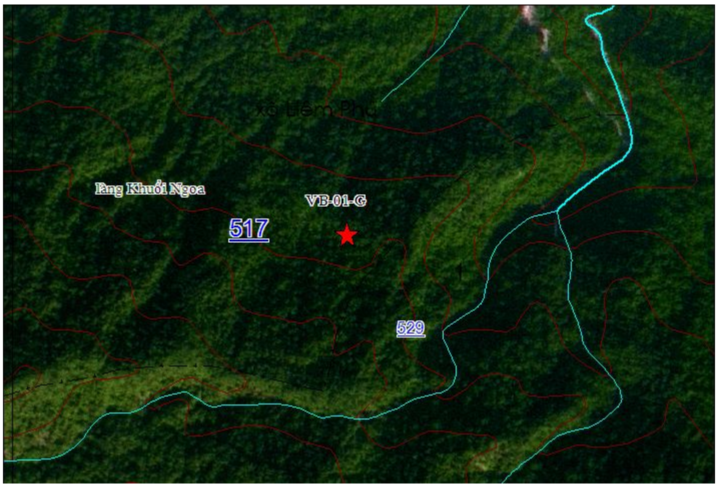


Figure 1: The position of sample plots LC-VB-01 on satellite image

Description of the sample plot LC-VB-03 is following:

Table 2: Description of the sample plot LC-VB-03

Plot name	LC-VB-03
Administrative location	Sub-compartment 1, compartment 517; Lũng Nặm village - Liêm Phú commune - Văn Bàn district - Lào Cai province
Coordinate (VN2000 projection)	Lat = 21°57’57” N; Long = 104°20’10” E
Altitude	690 m
Slope	31°
Plot area	1 ha
Plot size	100 x 100 (m)
Forest type	Evergreen broadleaved forest
Forest status	IIIA2
Volume (estimated)	250 m^3

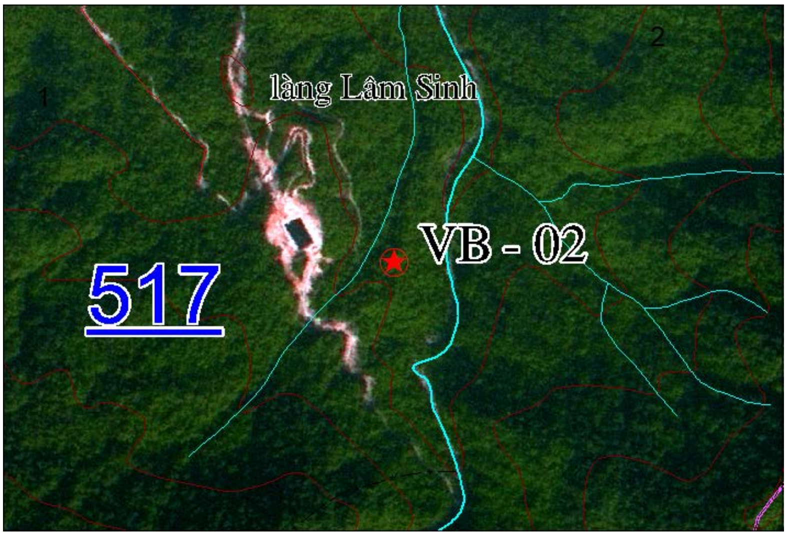


Figure 2: the position of the sample plot LC-VB-03 on satellite image

Table 3: Description of the sample plot BK-BT-01

Plot name	BK-BT-01
Administrative location	Sub-compartment 1, compartment 384; Nà Pán village - Đôn Phong commune - Bạch Thông district - Bắc Kạn province
Coordinate (VN2000 projection)	Lat = 22°10’32” N; Long = 105°43’45” E
Altitude	750 m
Slope	28°
Plot area	1 ha
Plot size	200 x 50 (m)
Forest type	Evergreen broadleaved forest
Forest status	IIIA3
Volume (estimated)	210 m^3

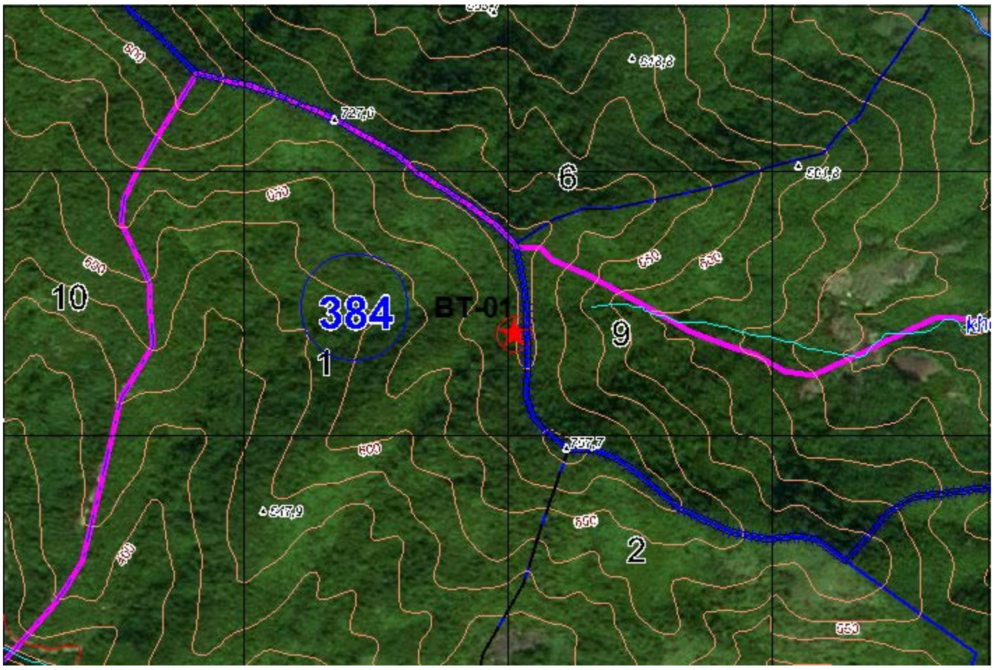


Figure 3: the position of the sample plot BK-BT-01 on satellite image

Table 4: Description of the sample plot BK-BT-02

Plot name	BK-BT-02
Administrative location	Sub-compartment 7, compartment 387; Mún I village - Dương Phong commune - Bạch Thông district - Bắc Kạn province
Coodinate (VN2000 projection)	Lat = 22°08’25” N; Long = 105°41’46” E
Altitude	580 m
Slope	32°
Plot area	1 ha
Plot size	100 x 100 (m)
Forest type	Evergreen broadleaved forest
Forest status	IIIA2
Volume (estimated)	190 m^3

Figure 4: the position of the sample plot BK-BT-02 on satellite image

Bamboo forest

The criteria for bamboo sample plot establishment are: i) representativeness (based on assessment of experts) of the forest types being studied; ii) representativeness for topographic conditions; and iii) covering a number of different bamboo sizes; iv) the sample plots should be set up on less disturbed area. The area for one bamboo sample plot is 0.5 ha, which is half of that for woody forest (because the variation in bamboo forests is often smaller than woody forests). The shape of the plot is rectangular (100m x 50m).

In the bamboo sample plots, four sub-plots with an area of 400 m^2 (20m x 20m) each were established at the four corners. DBHs were measured using diameter tapes and age classes (old, medium and young) were determined for each bamboo with DBH over 2cm in the sub-plots. The age class of a bamboo was determined as follows:

- Young class: bamboos with age of 1-2 years old and have inadequate development of branch and leaves. The stem is in deep blue, with down and no lichen on stem. The stem contains more water, is soft and white color inside. The sheaves of bamboo shoot remain on the stem.
- Medium-aged class: bamboos with ages of 2-3 years for Nua, Vau, Lo o; or of 3-4 years old for Luong, Dien, Tre. There are no sheaves on the stem and luxuriant branches and branches distributes mainly on the top of the stem. The color of stem and main branches skin is deep blue mixed with brownish yellow and there is spotted lichen on the stem.

- Old class: bamboos with ages of over 3 years old for Nua, Vau, Lo o and over 5 years old for Luong, Dien, Tre. The leaves are light bue and stems are bluish yellow or spotted whitish grey caused by strong development of lichen (70-80%) and the deep blue color for stem skin almost disappears.

After a bamboo is measured, the bamboo was marked with white paint to avoid missed or repeated measurement. The description of bamboo forest plot and their location is below.

Table 5: Description of the sample plot LC-VB-02A

Plot name	LC-VB-02A
Administrative location	Liêm Phú commune - Văn Bàn district - Lào Cai province
Coordinate (VN2000 projection)	Lat = 21°57’53” N; Long = 104°20’30” E
Altitude	600 m
Slope	25°
Plot area	5000 m^2
Plot size	100 x 50 (m)
Forest type	Bamboo (*Indosasa angustata*) forest (forest predominated by bamboo species)
Forest status	Medium
Density (estimated)	4500 trees/ha

Table 6: Description of the sample plot LC-VB-02B

Plot name	LC-VB-02B
Administrative location	Liêm Phú commune - Văn Bàn district - Lào Cai province
Coordinate (VN2000 projection)	Lat = 21°57’58” N; Long = 104°20’26” E
Altitude	550 m
Slope	20°
Plot area	5000 m^2
Plot size	100 x 50 (m)
Forest type	Bamboo (*Indosasa angustata*) forest (forest predominated by bamboo species)
Forest status	Medium
Density (estimated)	4500 trees/ha

Figure 5: The positions of sample plots LC-VB-02A and LC-VB-02B on satellite image

Table 7: Description of the sample plot BK-CM-01

Plot name	BK-CM-01
Administrative location	Sub-compartment 13, compartment 406; Ruộc village - Mai Lạp commune - Chợ Mới district - Bắc Kạn province
Coodinate (VN2000 projection)	Lat = 22°02’15” N; Long = 105°42’28” E
Altitude	345 m
Slope	18°
Plot area	5000 m2
Plot size	100 x 50 (m)
Forest type	Bamboo (*B. chirostachyoides*) forest
Forest status	Dense
Density (estimated)	13,800 trees/ha

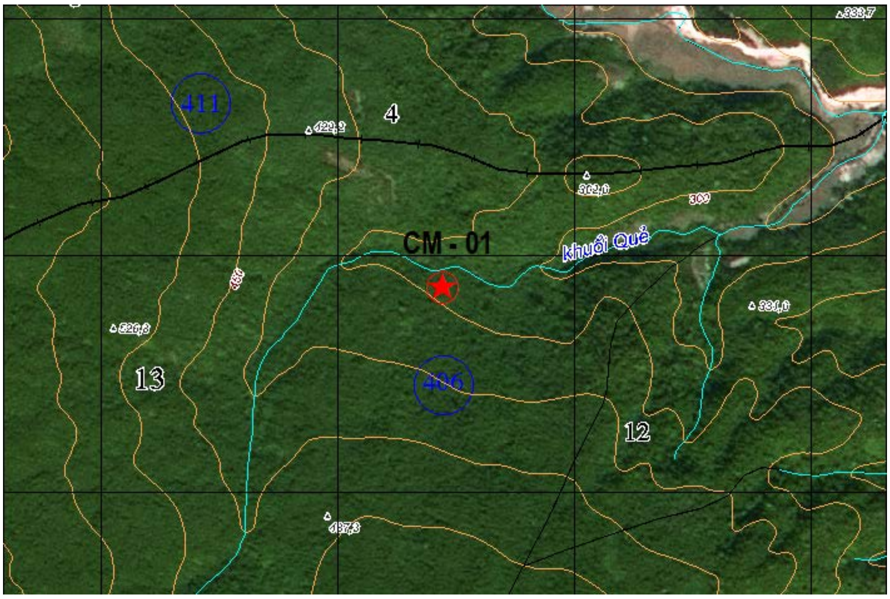


Figure 6: the position of the sample plot BK-CM-01 on satellite image

2.1.2 Selection of sample trees

Evergreen Boradlevead forest

All the trees in the sample plots were grouped into DBH classes. The interval of DBH classes is 10 cm, and the DBH classes are: 5 – 14.9 cm; 15 – 24.9 cm; 25 – 34.9 cm; 35 – 44.9 cm; 45 – 54.9 cm; 55 – 64.9 cm; 65 – 74.9 cm. The sample trees in each DBH class in the sample plots were randomly selected. The total number of sample trees for harvesting is 55 trees for each forest type (50 trees for development of allometric equations and 5 trees for validation). The number of sample trees for each DBH class is chosen proportionally with the number of trees in the class, with at least three sample trees harvested for each DBH class. Due to time and budget limitation, trees with DBH ≥ 75 cm were basically not sampled in this study.

Totally, biomass data of 215 sample trees are collected. The numbers of felled trees for each species and each DBH class are given in Table 8 and

Table 9, respectively.

Table 8: Number of felled trees divided by species in the four evergreen broadleaf sample plots

No	Local Name	Scientific Name	Number of felled trees				
			LC-VB-01	LC-VB-03	BC-BT-01	BC-BT-02	Total
1	Ba bét	*Mallotus paniculatus*			1		1
2	Bồ đề	*Styrax tonkinensis*			2	1	3
3	Bồ hòn Vân Nam	*Sapindus delavayi*	1				1
4	Bồ kết tây	*Albizia lebbeck*		1		1	2
5	Bọ muối	*Euodia sutchuenensis*	2				2

No	Local Name	Scientific Name	Number of felled trees				
			LC-VB-01	LC-VB-03	BC-BT-01	BC-BT-02	Total
6	Bời lời	*Litsea pierrei*	1				1
7	Bời lời nhớt	*Litsea glutinosa*				1	1
8	Bộp lông	*Actinodaphne pilosa*				1	1
9	Bứa	*Garcinia oblongifolia*		2		2	4
10	Chân chim	*Schefflera heptaphilla*		1	2		3
11	Chẹo tía	*Engelhardtia roxburghiana*		1	2	1	4
12	Choại	*Terminalia bellirica*	1				1
13	Côm	*Elaeocarpus tonkinensis*	2	2	6		10
14	Côm trâu	*Elaeocarpus floribundus*			2		2
15	Cứt ngựa	*Archidendron chevalieri*	2	1		7	10
16	Đào bánh xe	*Rhaphiolepis indica*			2		2
17	Dẻ	*Castanopsis sp.*	3	4	9	7	23
18	Dọc	*Garcinia multiflora*			1	1	2
19	Đu đủ rừng	*Trevesia palmata*			1		1
20	Dung giấy	*Symplocos laurina var. acuminata*		4		1	5
21	Giổi xanh	*Michelia mediocris*	1				1
22	Gội nếp	*Aglaia spectabilis*	2	3	1		6
23	Gù hương	*Cinnamomum balansae*			1		1
24	Hồ mộc răng hai	*Huodendron biaristatum*	1			1	2
25	Hoắc quang	*Wendlandia paniculata*				1	1
26	Hồng đạm lông	*Adinandra glischrolomavar*				1	1
27	Hồng đạm Tam Đảo	*Adinandra bockiana*		1	3	1	5
28	Kháo	*Cinnadenia paniculata*	7	1	2	2	12
29	Kổng sữa Bắc Bộ	*Eberhardtia tonkinensis*	1				1
30	Lá nến	*Macaranga denticulata*	3		2		5
31	Lõi thọ	*Gmelina arborea*				1	1
32	Lọng bàng	*Dillenia turbiana*	1				1
33	Lòng mang	*Pterospermum heterophyllum*				3	3
34	Mán đỉa Bắc Bộ	*Archidendron tonkinensis*	4		1		5
35	Mán đỉa trâu	*Archidendron lucidum*	1				1

No	Local Name	Scientific Name	Number of felled trees				
			LC-VB-01	LC-VB-03	BC-BT-01	BC-BT-02	Total
36	Màng tang	*Litsea cubeba*		1			1
37	Mít rừng	*Ficus vasculosa*		2			2
38	Mò quả to	*Cryptocarya impressa*	1				1
39	Mỡ trơn	*Paederia foetida*			2		2
40	Muồng hoa vàng	*Cassia ssp. Nodosa*			1		1
41	Ngát	*Gironniera subaequalis*	1	5	1	1	8
42	Ngô thù du lá trọc	*Tetradium glabrifolium*	2				2
43	Ớt sừng lá to	*Kitabalia macrophylla*		1			1
44	Re	*Cinnamomum tamala*				7	7
45	Re hương	*Cinnamomum parthenoxylon*			3	1	4
46	Re lục phấn	*Cinnamomum glaucescens*	1				1
47	Sâng	*Pometia pinnata*		1			1
48	Sến mủ	*Shorea roxburghii*		1			1
49	Sồi	*Lithocarpus sp.*			1		1
50	Sòi tía	*Sapium discolor*	1	4			5
51	Sơn vôi	*Semecarpus perniciosa*				1	1
52	Táu mật	*Vatica odorata ssp.brevipetiolata*	7	6			13
53	Táu mặt quỷ	*Hopea mollissima*				5	5
54	Thừng mực	*Holarrhena pobescens*		1			1
55	Trám	*Canarium sp.*	1	1	2		4
56	Trám chim	*Canarium parvum*				2	2
57	Trám mao	*Garuga pinnata*		1			1
58	Trâm sừng	*Syzygium chanlos*			1	4	5
59	Trâm trắng	*Syzygium wightianum*		1			1
60	Trâm vỏ đỏ	*Syzygium zeylanicum*		1			1
61	Trín	*Schima wallichii*	1				1
62	Trường vải	*Nephelium melliferum*		2			2
63	Vạng trứng	*Endospermum chinense*	2	1	1		4
64	Vỏ mản	*Ficus trivia*		1			1
65	Xoan đào tía	*Prunus arborea var.montana*		3	2	1	6

No	Local Name	Scientific Name	Number of felled trees				
			LC-VB-01	LC-VB-03	BC-BT-01	BC-BT-02	Total
66	Xoan nhừ	*Choerospondias axillaris*		1	3		4
Total			***50***	***55***	***55***	***55***	***215***

Table 9: Sampled trees in four evergreen broadleaf sample plots

No	DBH class	Number of felled trees				
		LC-VB-01	LC-VB-03	BC-BT-01	BC-BT-02	Total
1	5 – 14,9 cm	15	20	23	16	**74**
2	15 – 24,9 cm	12	9	9	11	**41**
3	25 – 34,9 cm	11	10	8	12	**41**
4	35 – 44,9 cm	6	8	7	7	**28**
5	45 – 54,9 cm	3	4	4	4	**15**
6	55 – 64,9 cm	1	3	2	2	**8**
7	≥ 65 cm	2	1	2	3	**8**
Total		***50***	***55***	***55***	***55***	***215***

Bamboo forest

Firstly, all bamboos were grouped into DBH classes. The interval of DBH class was either 1 cm (if the maximum DBH is less than 10 cm) or 2 cm otherwise. For the interval 1 cm, the DBH classes were: 2 – 2.9 cm; 3 – 3.9 cm; 4 – 4.9 cm; 5 – 5.9 cm; 6 – 6.9 cm; 7 – 7.9 cm; 8 – 8.9 cm; etc. For the interval 2 cm, the DBH classes were: 2 – 3.9 cm; 4 – 5.9 cm; 6 – 7.9 cm; 8 – 9.9 cm; 10 – 11.9 cm; 12 – 13.9 cm; 14 – 15.9 cm; etc. Next, the sample bamboos from each DBH class were randomly selected following the next crtiteria: i) Samples should be allocated in proportion with the number of bamboos in each DBH class; ii) Samples should be representative of the age class; iii) The number of samples would be determined based on the number of DBH classes identified, and the bamboo age. The total number of samples for harvesting is 120 (100 bamboos for development of allometric equations and 20 bamboos for validation).

Totally, biomass data of 70 sample bamboos are collected. The numbers of bamboos by DBH classes and age classes are given in Table 23. Data on species name, DBH, height, age class, and dry weight of each component of these sample bamboos are given in Annex 4.

Table 10: Numbers of sample bamboos by DBH classes and age classes

DBH Class	Age class			Total
	Old	Medium	Young	

4.0 - 5.9 cm	3	3	3	**9**
6.0 - 7.9 cm	5	4	3	**12**
8.0 - 9.9 cm	6	6	3	**15**
10.0 - 11.9 cm	9	7	3	**19**
12.0 - 13.9 cm	8	4	3	**15**
Total	**31**	**24**	**15**	**70**

2.2 Variables measurement and calculations for volume and biomass estimations

2.2.1 Field measurement of fresh biomass of sample trees

Evergreen Boradlevead forest

Firstly, the measurement point for DBH was marked, and then the tree was felled at its base following logging procedures. Following this, measuring tapes were used to measure:

a) Diameter and height of the stump;

b) DBH at 1.3 m;

c) Total tree height (from the stump to the top of the crown).

d) Length of tree bole - from the stump to the first main branch;

e) Length of tree bole - from the stump to the point where diameter becomes 10 cm;

After, the tree was separated into different components (stem, branches and leaves) and the weights of these components were weighed immediately in the field using a digital scale with the maximum capacity of 500 kg and the precision of 0.1 kg.

Sampling for dry mass analysis was done immediately after completion of measurement of fresh weight of each tree components. The following steps were conducted:

1. Samples for dry mass analysis: collect three samples per tree of stem, branches and leaves. The samples were taken from different positions of the stem, and different parts of branches and leaves so that they are representative for the parts being sampled. Following ICRAF (2011), the samples of the stem and branch were about 0.5 to 1.0 kg in weight. The samples of the leaves were about 0.3 – 0.5 kg in weight. The samples for dry mass analysis were weighted immediately and carefully using two digital scales (one is Ohaus BC15 with the maximum weighing capacity of 15 kg and the precision of 0.5 g and the other is Ohaus SPS2001F with the maximum weighing capacity of 2 kg and the precision of 0.1 g) to accurately determine the fresh weight of each sample.

2. Samples for wood density analysis: five wood discs were taken from the stem. The sampling positions were at stump level (0.0 m), at 1/5; 2/5; 3/5; and 4/5 of stem length. The wood discs were 5 – 10 cm thick. For small discs (diameter ≤ 20 cm), the whole disc

was taken as is. For large discs (diameter > 20 cm), only a radial section of the disc was taken.

Bamboo forest

First, the bamboo was felled using a hand saw. Next, the height of the felled bamboo was measured. Finally, the bamboo was separated into different components: stem, branches and leaves and the weights of each component were measured immediately using a scale.

For bamboo forests, only samples for dry mass analysis were collected. Samples were collected immediately after measurement of fresh weights of each bamboo component. Out of 120 sample bamboos for fresh biomass measurement, 70 samples were selected for sampling of dry mass analysis. The selected bamboos for sampling of dry mass analysis were representatives of each age group and DBH class. For each sample bamboo selected for dry mass analysis, six sub-samples were collected. Four sub-samples were taken from the stem (at the stump level; ¼; ½; and ¾ of stem length positions), one sub-sample from branches and one sub-sample from leaves. The sub-samples were collected such that their weights are 0.5 – 1.0 kg for stem and branches, and 0.3 – 0.5 kg for leaves. The sub-samples were then weighted immediately in the field using high a precision scale (Ohaus SPS2001F with the maximum weighing capacity of 2 kg and the precision of 0.1 g) to accurately determine their weights.

2.2.2 Laboratory measurement

After the completion of the destructive measurement in the field, the collected samples were sent immediately to laboratories in the Forest Science Institute of Vietnam (FSIV) for oven dry mass and wood density analyses. Dry mass of samples were determined using oven drier at a temperature of $105^{O}C$ until the samples reached constant weights. Wood density measurements methodology followed the National standard TCVN 8048-2: 2009. The wood volume was determined using the water displacement method with prism shaped and minimum sized: 20 x 20 x 25 mm subsamples. Wood densities was then calculated with the following formula:

$$SWD = \frac{SDW}{SV} \qquad \text{(Eq. 1)}$$

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

The total dry weights (TDW) for each component of the sample trees are calculated based on the total fresh weights of each component (TFW) measured in the field and the ratios of dry weight to fresh weight (SDW/SFW) calculated for each component in the laboratory. The formula for TDW calculation is as follows:

$$TDW_c = TFW_c \frac{SDW_c}{SFW_c} \qquad \text{(Eq. 2)}$$

Where: TDW_c is the total dry weight of a component *c* (stem, branches, or leaves); TFW_c is the total fresh weight of this component measured in the field; SDW_c and SFW_c are the dry weight and fresh weight and the samples for this component.

The total above-ground biomass of a tree is the sum of its total dry weights of three components: stem, branches and leaves. The formula is:

$$TDW_{tree} = TDW_{stem} + TDW_{branch} + TDW_{leave} \qquad \text{(Eq. 3)}$$

2.2.3 Other variables

2.3 Model fitting and selection

2.3.1 Regression Analysis

Regression analyses are conducted using the SAS software. For evergreen broadleaved forest, the variables include DBH (D, cm), height (H, m) and wood density (ρ, g/cm^3). The following nine models are used:

$AGB = aD^b$ (Model 1)

$AGB = a(D^2H)^b$ (Model 2)

$AGB = a(D^2H^{0.7})^b$ (Model 3)

$AGB = aD^bH^c$ (Model 4)

$AGB = a(D^{2.4}\rho)^b$ (Model 5)

$AGB = aD^b\rho^c$ (Model 6)

$AGB = a(D^2H\rho)^b$ (Model 7)

$AGB = a(D^2H^{0.7}\rho)^b$ (Model 8)

$AGB = aD^bH^c\rho^d$ (Model 9)

Where *a*, *b*, and *c* are the coefficients needed to be found. Models 3, 5 and 8 are based on the results of previous analyses using other datasets from the regression analysis for the stem volume equation using the form $V = aD^2H^b$ and $V = cD^d$, the optimal values for *b* and *d* are, respectively, approximately 0.7 and 2.4 (unpublished data).

For bamboo forest, the variables include DBH (D) and height (H). Models 1 to 4 above are used for regression analysis.

Three approaches of regression analysis were used to find the coefficients:

- The first approach is to apply the least squares optimization to the original equations.
- The second approach is to transform the above equations to the logarithmical form and then apply the least squares optimization to the transformed equations.
- The third approach is to use the maximum likelihood optimization to the original equations.

2.3.2 Comparison of models

In order to evaluate the in-sample performance of the models, three indicators were employed: the adjusted R^2 ($\bar{R}^2$), the sum of squared error (SSE) and Akaike information criterion with correction (AICc, Burnham and Anderson 2002). The AICc is calculated by the following formula:

$$AIC_c = -2\ln(L) + \frac{2kn}{n-k-1} \quad \text{(Eq. 4)}$$

Where L is the maximum likelihood of the model, k is the number of parameters needed to be estimated, and n is the size of the sample dataset.

The $\bar{R}^2$ and SSE are used to measure the goodness of fit for equations that are developed using the least squares method. The AICc is used to measure the goodness of fit for equations that are developed using the maximum likelihood method.

2.3.3 Cross validation and error assessment

To avoid over fitting of the models, cross validation tests were conducted. The sample dataset is randomly divided into two sub-sets: a training subset and a testing sub-set. The sizes of the training and testing sub-set are, respectively, 2/3 and 1/3 the size of the original dataset. For each division, the training sub-set was used to fit the models and then the fitted models were used to predict the total dry weights of the testing sub-set. These predicted total dry weights were then used to calculate the errors (in percentage) as compared to the measured total dry weight of the testing sub-set. The above procedure was repeated one million times to generate probability density functions of the total AGB error of each equation. Each probability density function was then approximated by a log-normal distribution (Eq. 4) in order to compare the performance of the equations in practice and estimate the confidence intervals of the error for each equation.

$$f_x(x;\alpha,\sigma,\mu) = \frac{\alpha}{(\alpha x+1)\sigma\sqrt{2\pi}} \times e^{-\frac{(\ln(\alpha x+1)-\mu)^2}{2\sigma^2}} \qquad \text{(Eq. 5)}$$

To facilitate the cross validation tests, a program was written in the C language. The program was validated by comparing its results with the SAS software. With the same dataset, the program generated the same results with the SAS software for every combination of the statistical models and regression approaches.

3 RESULT FOR EVERGREEN BROADLEAF FOREST

3.1 Result 1: forest and tree characterisitics

3.1.1 Forest characteristics: species composition and forest structure

Tree species composition

Totally 143 species are found in the four sample plots. A summary of species composition is provided in Table 11. The detailed species composition is given in Annex 2.

Table 11: Summary of tree species composition in the studied area

No	Local name	Scientific name	N	N%	G%	IV%
1	Dẻ	*Castanopsis sp.*	258	9.08	13.49	11.28
2	Kháo	*Cinnadenia paniculata*	247	8.69	9.17	8.93
3	Táu mật	*Vatica odorata ssp.brevipetiolata*	181	6.37	7.13	6.75
4	Côm	*Elaeocarpus tonkinensis*	185	6.51	3.81	5.16
5	Táu mặt quỷ	*Hopea mollissima*	121	4.26	5.08	4.67
6	Dung giấy	*Symplocos laurina var. acuminata*	122	4.29	1.72	3.01
7	Gội nếp	*Aglaia spectabilis*	72	2.53	3.02	2.78
8	Trâm vỏ đỏ	*Syzygium zeylanicum*	81	2.85	1.81	2.33
9	Cứt ngựa	*Archidendron chevalieri*	41	1.44	2.99	2.22
10	Hoắc quang	*Wendlandia paniculata*	84	2.96	1.05	2.00
		Total		48.98	49.27	

N: Number of trees; N%: number of trees percentage; G%: basal area percentage; IV%: Important value

Based on the IV% index, the 10 most dominant species are *Castanopsis sp., Cinnadenia paniculata, Vatica odorata ssp. brevipetiolata, Elaeocarpus tonkinensis, Hopea mollissima, Symplocos laurina var. acuminata, Aglaia spectabilis, Syzygium zeylanicum, Archidendron chevalieri, and Wendlandia paniculata*. These species account for 48.98% of the total trees and 49.27% of the total basal area.

Forest structure

There are totally 2,842 trees in the four studied sample plots. The average density is 710 trees/ha. The N-D distribution of all the trees in the four studied sample plots is given in Figure 7. It can be seen that the number of trees is decreasing when DBH gets larger. Trees having DBH ≥ 45 cm only accounts for 3.2% of the total trees.

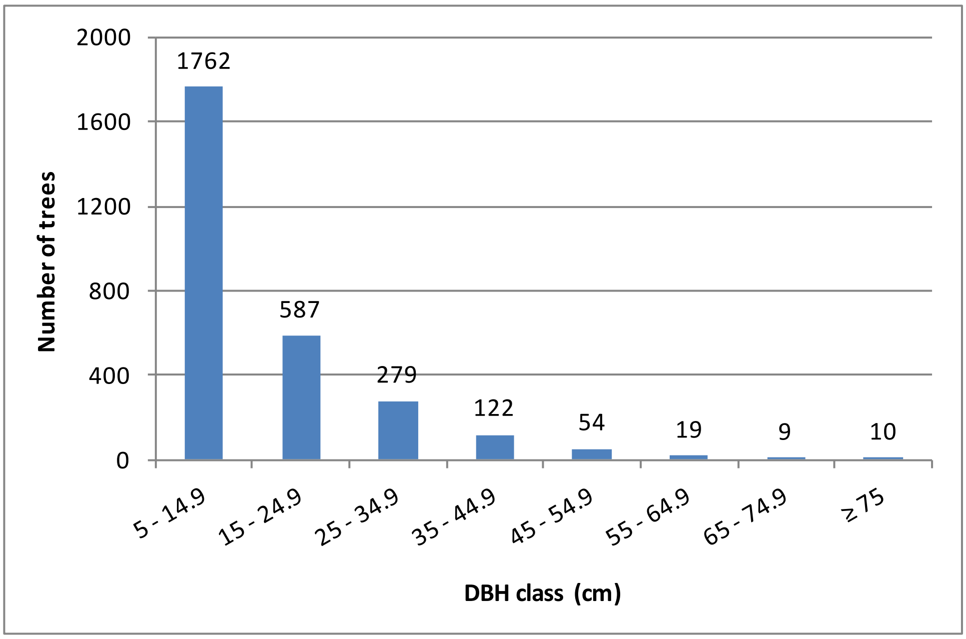


Figure 7: N-D distribution of the trees in four evergreen broadleaf sample plots

3.1.2 D-H correlation analysis

We used the SAS software to do a regression analysis of the logarithm function correlating H(m) and DBH (cm). The resulted equation is H_m = -9.5378 + 9.1452 × ln(DBH_cm) (Figure 8). The F value is 992.94 and the function is significant at p<0.001 level.

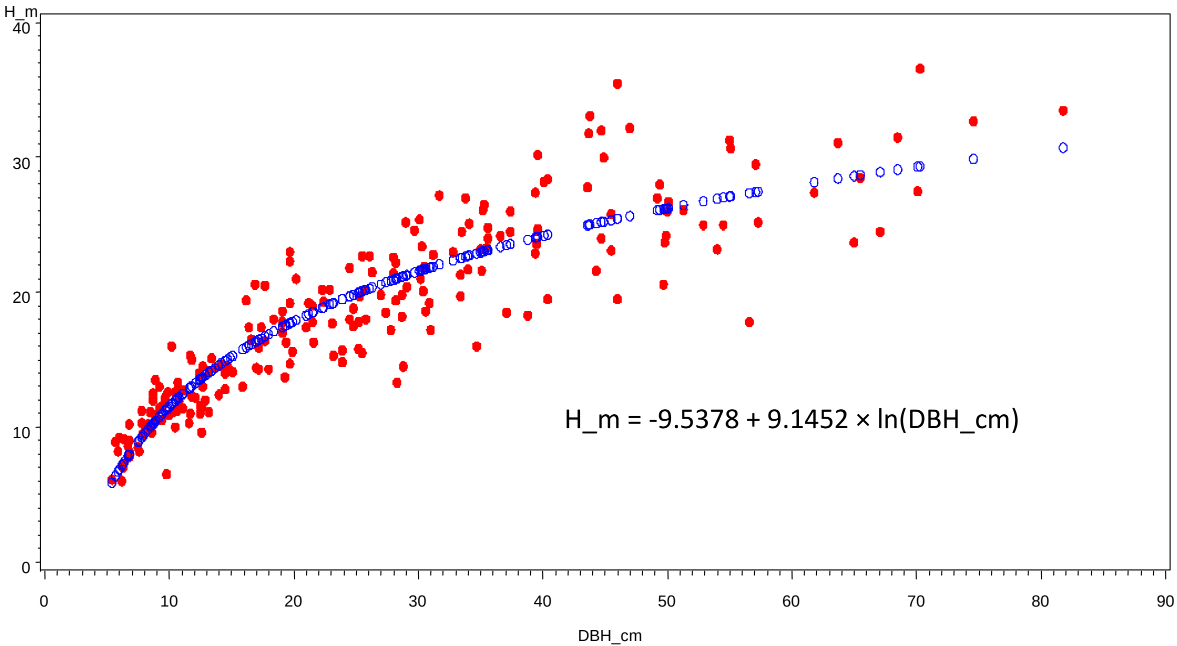


Figure 8: Correlation function between H (m) and DBH (cm)

3.1.3 Wood density

Table 12 below provides a summary of wood density analysis results for the species in the sample dataset. The average wood density is 0.560±0.169. The minimal value founded for the sampled trees is 0.254 and the maximum is 0.963. For those species that have previous known values, the wood densities analyzed in this Study agrees quite well. However, there are some cases where the differences between the WD values in this Study and the previous known values are quite large, such as the case of *Shorea roxburghii* (no. 48). The reasons may be because of mis-identifying the species name, small number of sample trees, or mistakes in the analysis process. Note that due to the limitation of time, the wood densities of sample trees in two sample plots BK-BT-01 and BK-BT-02 are only analyzed based on a small (often 5 or 6) number of sub-samples of the wood discs. As a result, the WD values of these trees are not as reliable as the WD values in plots LC-VB-01 and LC-VB-03.

Table 12: Results of wood density analysis for species in the sample dataset

No	Vietnamese Name	Scientfic Name	*N*	Wood density (g/cm^3)			
				Min	Max	Avg	Known value*
1	Ba bét	*Mallotus paniculatus*	1	0.371	0.371	0.371	
2	Bồ đề	*Styrax tonkinensis*	3	0.326	0.420	0.372	0.430
3	Bồ hòn Vân Nam	*Sapindus delavayi*	1	0.322	0.322	0.322	
4	Bồ kết tây	*Albizia lebbeck*	2	0.698	0.770	0.734	
5	Bọ muối	*Euodia sutchuenensis*	2	0.259	0.378	0.319	
6	Bời lời	*Litsea pierrei*	1	0.395	0.395	0.395	
7	Bời lời nhớt	*Litsea glutinosa*	1	0.674	0.674	0.674	
8	Bộp lông	*Actinodaphne pilosa*	1	0.328	0.328	0.328	
9	Bứa	*Garcinia oblongifolia*	4	0.647	0.721	0.683	0.710
10	Chân chim	*Schefflera heptaphilla*	3	0.378	0.509	0.432	
11	Chẹo tía	*Engelhardtia roxburghiana*	4	0.409	0.690	0.538	0.400
12	Choại	*Terminalia bellirica*	1	0.472	0.472	0.472	0.700
13	Côm	*Elaeocarpus tonkinensis*	10	0.463	0.652	0.557	0.670
14	Côm trâu	*Elaeocarpus floribundus*	2	0.451	0.616	0.534	
15	Cứt ngựa	*Archidendron chevalieri*	10	0.408	0.598	0.498	
16	Đào bánh xe	*Rhaphiolepis indica*	2	0.756	0.945	0.850	
17	Dẻ	*Castanopsis sp.*	23	0.377	0.912	0.642	
18	Dọc	*Garcinia multiflora*	2	0.535	0.745	0.640	
19	Đu đủ rừng	*Trevesia palmata*	1	0.410	0.410	0.410	
20	Dung giấy	*Symplocos laurina var. acuminata*	5	0.516	0.833	0.651	0.590
21	Giổi xanh	*Michelia mediocris*	1	0.327	0.327	0.327	0.580
22	Gội nếp	*Aglaia spectabilis*	6	0.401	0.693	0.492	

No	Vietnamese Name	Scientfic Name	*N*	Wood density (g/cm^3)			
				Min	Max	Avg	Known value*
23	Gù hương	*Cinnamomum balansae*	1	0.510	0.510	0.510	0.650
24	Hồ mộc răng hai	*Huodendron biaristatum*	2	0.406	0.719	0.563	
25	Hoắc quang	*Wendlandia paniculata*	1	0.686	0.686	0.686	
26	Hồng đạm lông	*Adinandra glischrolomavar*	1	0.598	0.598	0.598	
27	Hồng đạm Tam Đảo	*Adinandra bockiana*	5	0.390	0.738	0.565	
28	Kháo	*Cinnadenia paniculata*	12	0.362	0.594	0.475	
29	Kồng sữa Bắc Bộ	*Eberhardtia tonkinensis*	1	0.373	0.373	0.373	0.480
30	Lá nến	*Macaranga denticulata*	5	0.300	0.448	0.376	0.580
31	Lõi thọ	*Gmelina arborea*	1	0.432	0.432	0.432	0.698
32	Lọng bàng	*Dillenia turbiana*	1	0.560	0.560	0.560	
33	Lòng mang	*Pterospermum heterophyllum*	3	0.637	0.693	0.668	
34	Mán đỉa Bắc Bộ	*Archidendron tonkinensis*	5	0.254	0.497	0.386	
35	Mán đỉa trâu	*Archidendron lucidum*	1	0.404	0.404	0.404	
36	Màng tang	*Litsea cubeba*	1	0.411	0.411	0.411	
37	Mít rừng	*Ficus vasculosa*	2	0.361	0.478	0.420	
38	Mò quả to	*Cryptocarya impressa*	1	0.559	0.559	0.559	
39	Mỡ trơn	*Paederia foetida*	2	0.292	0.405	0.349	
40	Muồng hoa vàng	*Cassia ssp. Nodosa*	1	0.517	0.517	0.517	
41	Ngát	*Gironniera subaequalis*	8	0.397	0.688	0.494	0.570
42	Ngô thù du lá trọc	*Tetradium glabrifolium*	2	0.295	0.341	0.318	
43	Ớt sừng lá to	*Kitabalia macrophylla*	1	0.556	0.556	0.556	
44	Re	*Cinnamomum tamala*	7	0.571	0.748	0.681	
45	Re hương	*Cinnamomum parthenoxylon*	4	0.372	0.526	0.475	
46	Re lục phấn	*Cinnamomum glaucescens*	1	0.335	0.335	0.335	
47	Sâng	*Pometia pinnata*	1	0.576	0.576	0.576	
48	Sến mủ	*Shorea roxburghii*	1	0.508	0.508	0.508	0.890
49	Sồi	*Lithocarpus sp.*	1	0.770	0.770	0.770	
50	Sòi tía	*Sapium discolor*	5	0.325	0.435	0.381	0.770
51	Sơn vôi	*Semecarpus perniciosa*	1	0.550	0.550	0.550	
52	Táu mật	*Vatica odorata ssp.brevipetiolata*	13	0.715	0.963	0.801	0.860
53	Táu mặt quỷ	*Hopea mollissima*	5	0.870	0.960	0.921	
54	Thừng mực	*Holarrhena pobescens*	1	0.437	0.437	0.437	

No	Vietnamese Name	Scientfic Name	*N*	Wood density (g/cm^3)			
				Min	Max	Avg	Known value*
55	Trám	*Canarium sp.*	4	0.442	0.605	0.501	
56	Trám chim	*Canarium parvum*	2	0.581	0.594	0.587	
57	Trám mao	*Garuga pinnata*	1	0.601	0.601	0.601	
58	Trâm sừng	*Syzygium chanlos*	5	0.570	0.963	0.800	0.920
59	Trâm trắng	*Syzygium wightianum*	1	0.797	0.797	0.797	
60	Trâm vỏ đỏ	*Syzygium zeylanicum*	1	0.838	0.838	0.838	
61	Trín	*Schima wallichii*	1	0.490	0.490	0.490	0.600
62	Trường vải	*Nephelium melliferum*	2	0.592	0.882	0.737	0.910
63	Vạng trứng	*Endospermum chinense*	4	0.300	0.428	0.344	0.480
64	Vỏ mản	*Ficus trivia*	1	0.686	0.686	0.686	
65	Xoan đào tía	*Prunus arborea var.montana*	6	0.343	0.547	0.445	0.620
66	Xoan nhừ	*Choerospondias axillaris*	4	0.464	0.590	0.514	

* These values are taken from the wood density database collected by RCFEE in the initial phase of this Study.

3.2 Result 2: stem volume modeling

The stem volume has not been measured during the field work so no model has been developed.

3.3 Result 3: modeling of Aboveground biomass

3.3.1 Modeling per tree compartments

Allometric equations for each component (stem, branches ans leaves) of the tree are developed. Only the power model which uses the input variable D (Model 1) is used here. The regression analyses are done using the procedure NLIN in the SAS software. The results are given in Table 13, Figure 9, Figure 10 and Figure 11 below.

Table 13: Non-linear regression results relating dry biomass (in kg) of each part of the tree with DBH (cm) using Model1

Part of tree	Parameter a				Parameter b				R^2	Pr > F
	Estimate	Std. err.	95% CL		Estimate	Std. err.	95% CL			
Stem	0.1274	0.0421	0.0445	0.2103	2.3655	0.0810	2.2059	2.5252	0.8686	<.0001
Branch	0.0102	0.0060	-0.0016	0.0220	2.5848	0.1423	2.3042	2.8653	0.7188	<.0001
Leaf	0.0785	0.0356	0.0084	0.1487	1.4696	0.1160	1.2409	1.6982	0.5330	<.0001

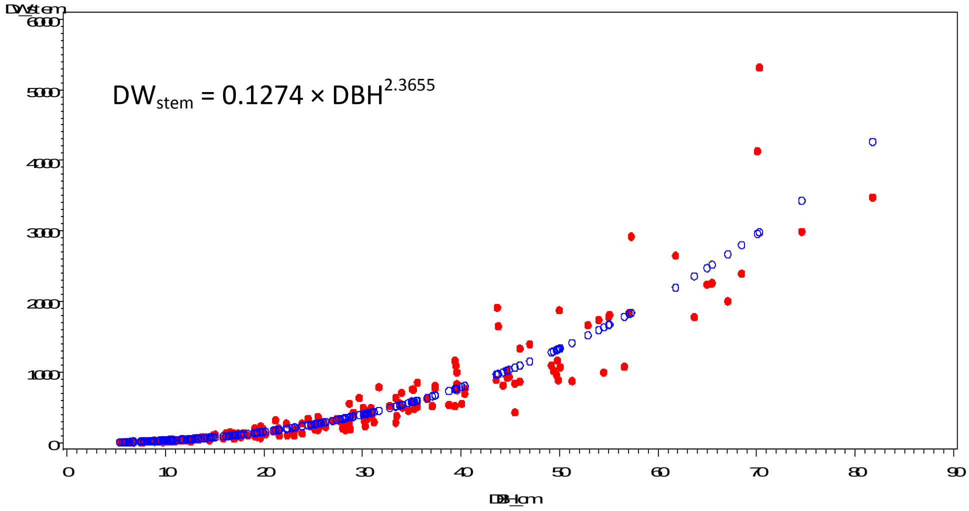


Figure 9: Allometric equation for estimating stem dry biomass from DBH (cm).

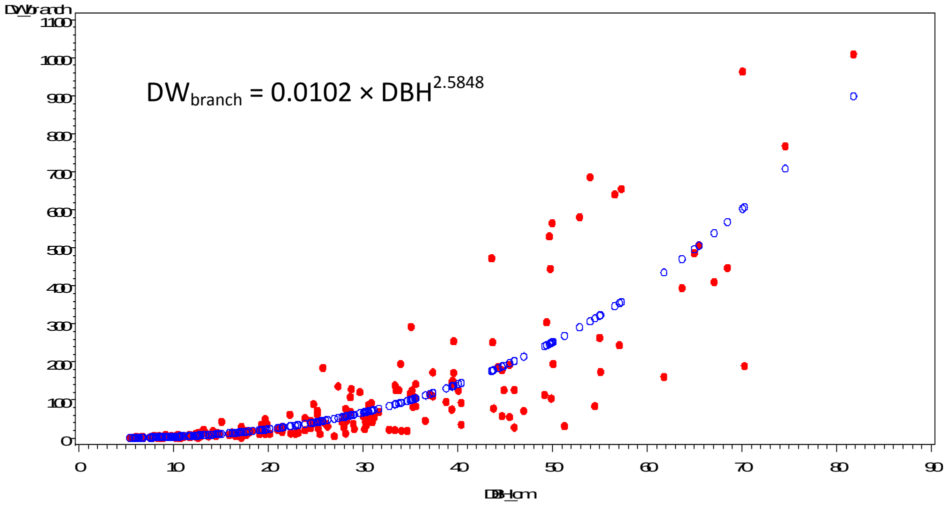


Figure 10: Allometric equation for estimating branch dry biomass from DBH (cm)

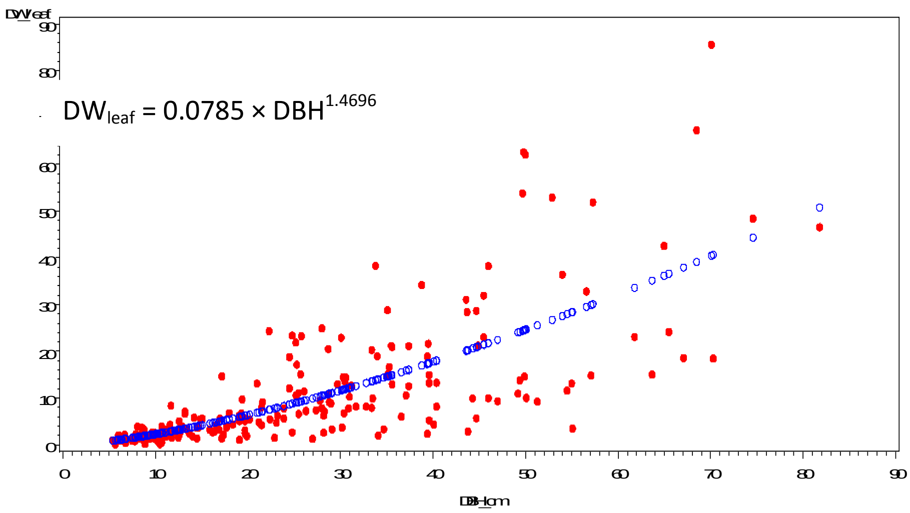


Figure 11: Allometric equation for estimating leave dry biomass from DBH (cm)

It can be observed from the above figures that stem biomass correlates strongest to the DBH, followed by branch biomass. Leaf biomass has weak correlation with DBH (R^2 = 0.533).

3.3.2 Modeling of total aboveground biomass

Model fitting

First, regression analyses using the first approach (least squares optimization of the original equations) for the 9 statistical models described in Section 2.5 are applied using the procedure NLIN in the SAS software. The analyzed results are given in Table 14.

Table 14: Results of regression analyses using the first approach (evergreen broadleaf)

No	Model	*a**	*b**	*c**	*d**	$\bar{R}^2$	SSE	Pr > F
1	$B = aD^b$	0.1428	2.3850			0.8947	17,809,040	<.0001
2	$B = a(D^2H)^b$	0.0335	0.9713			0.8952	17,730,794	<.0001
3	$B = a(D^2H^{0.7})^b$	0.0469	1.0328			0.8992	17,050,790	<.0001
4	$B = aD^bH^c$	0.0654	2.1747	0.4913		0.9000	16,843,037	<.0001
5	$B = a(D^{2.4}\rho)^b$	0.4093	0.9294			0.9430	9,636,757	<.0001
6	$B = aD^b\rho^c$	0.2675	2.3181	0.7464		0.9464	9,065,599	<.0001
7	$B = a(D^2H\rho)^b$	0.0919	0.9215			0.9583	7,053,671	<.0001
8	$B = a(D^2H^{0.7}\rho)^b$	0.1411	0.9707			0.9582	7,067,512	<.0001
9	$B = aD^bH^c\rho^d$	0.0925	2.0105	0.7030	0.8049	0.9608	6,576,661	<.0001

* All parameters are significant at $p < 0.001$.

All equations have quite high $\bar{R}^2$ value, indicating that they can all be used to estimate forest biomass. Equation derived from Model 1 has the lowest $\bar{R}^2$, as it uses only the predictor D. However, this model is still useful because H and ρ are hard and costly to measure and the $\bar{R}^2$ of this model is only 6.8% off of the best model. Models that use only D and H as the input variables have slightly higher $\bar{R}^2$ as compared to Model 1, suggesting that the inclusion of H does not improve the prediction reliability much. Models that use ρ as an additional input variable (Models from 5 to 10) have significantly higher $\bar{R}^2$ as compared to Models that do not use ρ (Models from 1 to 4), indicating that the inclusion of ρ can significantly improve the certainty of the prediction. Among the three models that use only two input variables D and H, Model 4 has the highest $\bar{R}^2$. Between the two models that use only D and ρ, Model 6 performs better. Models from 7 to 9, which use all three input variables, have the highest $\bar{R}^2$. Among these three, Model 9 has the highest $\bar{R}^2$.

Next, regression analyses using the second approach (least squares optimization of the logarithmically transformed forms) are performed using the procedure NLIN in the SAS software. The analyzed results are provided in Table 15.

Table 15: Results of regression analyses using the second approach (evergreen broadleaf)

No	Model	*a**	*b**	*c**	*d**	$\bar{R}^2$	SSE	Pr > F
1	$B = aD^b$	0.1082	2.4475			0.9665	20.107	<.0001

No	Model	*a**	*b**	*c**	*d**	$\bar{R}^2$	SSE	Pr > F
2	$B = a(D^2H)^b$	0.0351	0.9612			0.9687	18.766	<.0001
3	$B = a(D^2H^{0.7})^b$	0.0461	1.0288			0.9696	18.252	<.0001
4	$B = aD^bH^c$	0.0514	2.1109	0.6241		0.9695	18.207	<.0001
5	$B = a(D^{2.4}\rho)^b$	0.2661	0.9807			0.9856	8.654	<.0001
6	$B = aD^b\rho^c$	0.2176	2.3825	0.7996		0.9866	8.014	<.0001
7	$B = a(D^2H\rho)^b$	0.0836	0.9292			0.9897	6.204	<.0001
8	$B = a(D^2H^{0.7}\rho)^b$	0.1173	0.9898			0.9895	6.286	<.0001
9	$B = aD^bH^c\rho^d$	0.0967	2.0084	0.6913	0.8143	0.9904	5.686	<.0001

* All parameters are significant at $p < 0.001$.

It can be observed that the order of the models (ranked by $\bar{R}^2$) using the second approach is similar to that using the first approach. There is one difference: Model 3 is now the best among three models that use only D and H.

Finally, regression analyses using the third approach (maximum likelihood optimization) are done by the procedure NLP in the SAS software. The analyzed results are given in Table 16.

Table 16: Results of regression analyses using the third approach (evergreen broadleaf)

No	Model	*a**	*b**	*c**	*d**	Log*L*	AICc
1	$B = aD^b$	0.1142	2.4451			-1188.62	2381.30
2	$B = a(D^2H)^b$	0.0366	0.9599			-1181.73	2367.52
3	$B = a(D^2H^{0.7})^b$	0.0483	1.0278			-1178.87	2361.79
4	$B = aD^bH^c$	0.0547	2.1148	0.6131		-1178.56	2363.24
5	$B = a(D^{2.4}\rho)^b$	0.2496	0.9884			-1093.73	2191.51
6	$B = aD^b\rho^c$	0.2148	2.3938	0.8056		-1085.15	2174.36
7	$B = a(D^2H\rho)^b$	0.0787	0.9347			-1059.49	2123.03
8	$B = a(D^2H^{0.7}\rho)^b$	0.1092	0.9970			-1060.59	2125.23
9	$B = aD^bH^c\rho^d$	0.0970	2.0282	0.6731	0.8118	-1048.55	2105.28

* All parameters are significant at $p < 0.001$.

It can be observed that the coefficients estimated using the third regression methods are quite similar with those estimated using the second regression method. The order of the models (ranked by AICc) is also similar to that ranked by $\bar{R}^2$ in the second regression method. (Note that for AICc, the lower is the better.) Model 1, which uses only D as the input variable, has the worst AICc value. Models that use only two variables D and ρ (Models 5 and 6) perform much better than models that use only two variables D and H (Models 2, 3 and 4) in terms of AICc, suggesting that the inclusion of ρ is more important than the inclusion of H in improving the certainty of the prediction. Among the three models that use only D and H, Model 3 has the best AICc value. Between the two models that use only D and ρ, Model 6 performs better. Finally, Models from 7 to 9, which use all three input variables, have the best AICc values. Among them, Model 9 is the best.

Cross validation and error assessment

To avoid over-fitting of the models, we carried out cross validation tests as described in Section 2.7. Table 17 shows the properties of the approximated probability density functions of the total AGB error for every equations developed using the first approach.

Table 17: Properties of the probability density functions of the total AGB error (%) for the equations developed using the first regression approach (evergreen broadleaf)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0093	0.0710	0.0050	0.8147	0.5412	-0.0037	0.0520	0.9998	-13.54	16.73	30.27
2	0.0075	0.0585	0.0046	0.8462	0.6168	0.1591	0.0510	0.9997	-13.90	16.90	30.80
3	0.0080	0.0606	0.0049	0.8475	0.6166	0.1560	0.0525	0.9998	-13.45	16.46	29.91
4	0.0095	0.0744	0.0020	0.4994	0.2080	-0.3725	0.0511	0.9997	-14.07	16.72	30.79
5	0.0186	0.1001	-0.0018	0.1737	-0.0958	-0.6307	0.0746	0.9999	-9.66	11.54	21.20
6	0.0152	0.0836	-0.0129	-0.6193	-0.8465	-1.2986	0.0737	0.9999	-10.66	10.71	21.37
7	0.0095	0.0453	0.0027	0.3930	0.2848	0.0687	0.0836	0.9998	-8.67	10.08	18.75
8	0.0134	0.0632	0.0017	0.2782	0.1286	-0.1697	0.0845	0.9999	-8.60	10.00	18.60
9	0.0116	0.0574	-0.0061	-0.3819	-0.5229	-0.8043	0.0814	0.9999	-9.62	9.66	19.28

It can be seen that all models have very high R^2, indicating that Eq. 5 (in Section 2.7) is a good form to approximate the probability density functions of the total AGB error. In this table, the means (or expected values) of error indicate the accuracy while the ranges of error show the robustness of the models. Model 1, which uses only D as the input variable, is among the least accurate and least robust models (the expected value of error is 0.815% and the range of error is from -13.54% to 16.73%). Models that use H as an additional input variable (Models 2, 3 and 4) do not clearly improve the accuracy nor the robustness of the prediction. Among them, Model 4, although slightly less robust than Model 3, is the most accurate and should be chosen as representative for the group of two input variables D and H. Models that use only D and ρ (Models 5 and 6) are in general more accurate (i.e., their means are closer to zero) and have smaller ranges of error as compared to previous models, confirming the importance of using ρ as an variable for biomass estimation. Between these two, Model 5 is slightly more accurate and robust. Finally, Models from 7 to 9, which use all three predictors, are the most robust and in general quite accurate. Among these three, Model 8 performs the best in both terms of accuracy and robustness. The probability density functions of error for models which are representatives for each group of input variables are shown in Figure 12.

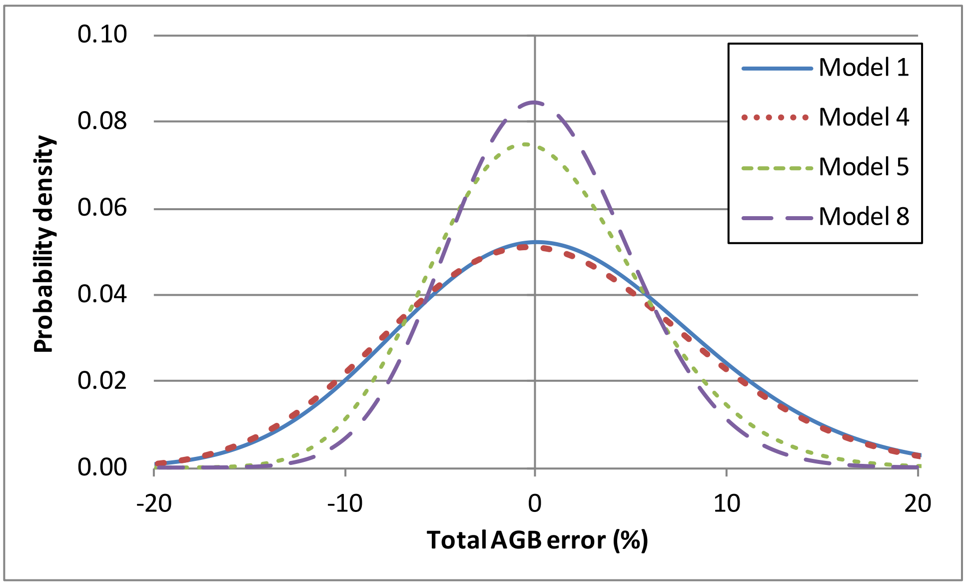


Figure 12: Probability density functions of the total AGB error (%) for some selected equations developed by the first regression approach (evergreen broadleaf)

Next, the cross validation test is performed for equations derived using the second regression approach. The results are provided in Table 18.

Table 18: Properties of the probability density functions of the total AGB error (%) for the equations developed using the second regression approach (evergreen broadleaf)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0105	0.0717	-0.0357	-3.0988	-3.3352	-3.8062	0.0608	0.9998	-15.37	10.52	25.89
2	0.0111	0.0753	-0.0637	-5.3421	-5.5830	-6.0627	0.0626	0.9998	-17.22	7.91	25.13
3	0.0111	0.0738	-0.0566	-4.7363	-4.9688	-5.4317	0.0636	0.9998	-16.45	8.30	24.75
4	0.0110	0.0732	-0.0534	-4.5175	-4.7496	-5.2119	0.0631	0.9998	-16.32	8.60	24.92
5	0.0171	0.0869	0.0229	1.5862	1.3596	0.9088	0.0769	0.9998	-8.03	12.49	20.52
6	0.0172	0.0845	0.0143	1.0463	0.8353	0.4155	0.0803	0.9999	-8.17	11.46	19.63
7	0.0108	0.0448	-0.0134	-1.1481	-1.2399	-1.4232	0.0974	0.9998	-8.93	7.16	16.09
8	0.0139	0.0583	-0.0059	-0.3002	-0.4219	-0.6648	0.0958	0.9998	-8.14	8.24	16.38
9	0.0131	0.0541	-0.0115	-0.7603	-0.8708	-1.0914	0.0979	0.9999	-8.46	7.57	16.03

It can be observed that equations developed using the second regression approach are more robust than those derived from the first regression method (i.e., having smaller ranges of error). However, they are in general less accurate than those derived from the first regression method. Among the three models that use only variables D and H, Model 4 is the most accurate (although having slightly larger range of error than Model 3) and should be chosen as representative for this input group. Between the two models that use only variables D and ρ, Model 6 is more accurate and robust. Among the three models that use all three input variables, Model 8 is the most accurate (although having slightly larger range of error than the two others) and should be chosen. The probability density functions of the equations derived from Models 1, 4, 6 and 8, which are representatives for each group of input variables, are shown in Figure 13.

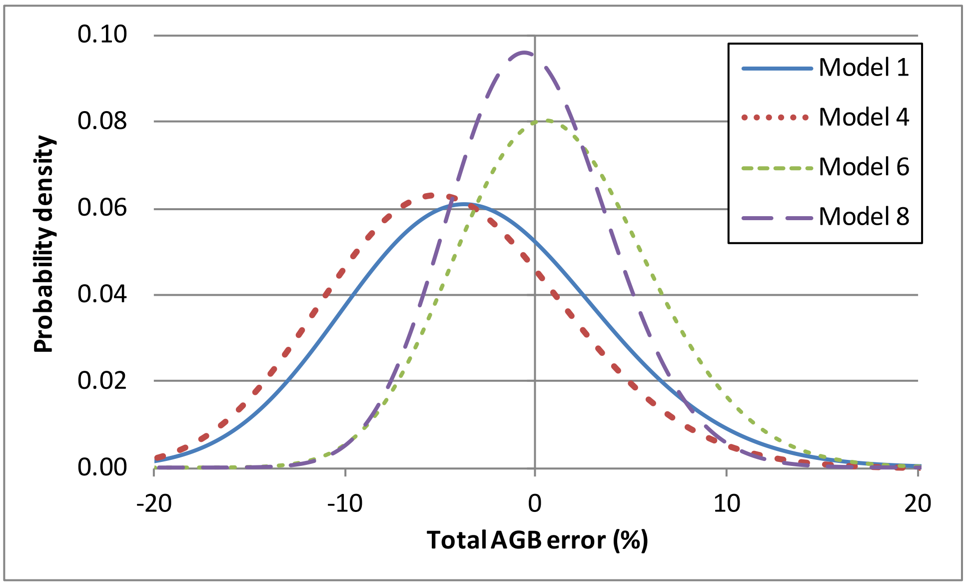


Figure 13: Probability density functions of the total AGB error (%) for some selected equations developed by the second regression approach (evergreen broadleaf)

Finally, the cross validation test is performed for equations developed using the third regression approach and the results are provided in Table 19.

Table 19: Properties of the probability density functions of the total AGB error (%) for the equations developed by the third regression approach (evergreen broadleaf)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0086	0.0593	0.0090	1.2603	1.0535	0.6409	0.0573	0.9996	-11.85	15.55	27.40
2	0.0110	0.0746	-0.0349	-2.8714	-3.1160	-3.6033	0.0611	0.9997	-15.06	10.71	25.77
3	0.0102	0.0680	-0.0142	-1.1538	-1.3776	-1.8235	0.0609	0.9998	-13.43	12.39	25.82
4	0.0097	0.0657	-0.0076	-0.5614	-0.7814	-1.2201	0.0598	0.9997	-13.08	13.21	26.29
5	0.0159	0.0819	0.0264	1.8923	1.6760	1.2457	0.0759	0.9998	-7.88	12.89	20.77
6	0.0133	0.0647	0.0483	3.8841	3.7185	3.3883	0.0782	0.9998	-5.69	14.40	20.09
7	0.0118	0.0493	-0.0192	-1.5131	-1.6140	-1.8155	0.0976	0.9999	-9.26	6.81	16.07
8	0.0148	0.0629	-0.0118	-0.6642	-0.7963	-1.0597	0.0952	0.9998	-8.54	7.96	16.50
9	0.0111	0.0462	0.0132	1.2963	1.1987	1.0038	0.0944	0.9998	-6.73	9.87	16.60

Equations developed using the third regression method are in general less robust (i.e., having larger ranges of error) than those derived by the second approach. Among the three models that use D and H as the input variable, Model 4 is the most accurate and should be chosen. Between the two models that use D and ρ as the input variables, Model 5 has slightly larger range of error but is much more accurate than Model 6 and should be selected. Among the three models that use all three input variables, Model 8 is the most accurate. The probability density functions of the equations derived from Models 1, 4, 5 and 8 using the third regression approach are shown in Figure 14.

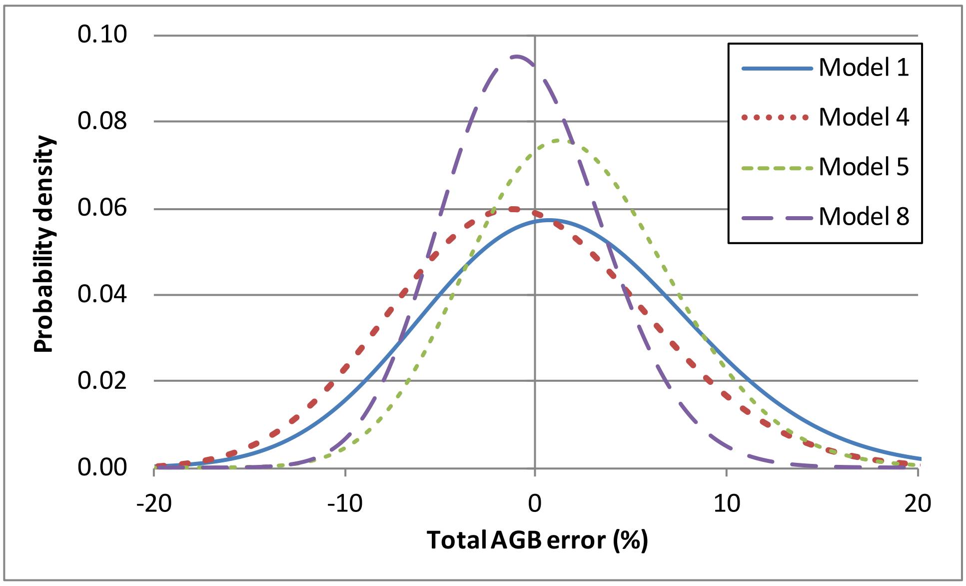


Figure 14: Probability density functions of the total AGB error (%) for some selected equations developed by the third regression approach (evergreen broadleaf)

In order to find the best equations for each group of input variables, we did a comparison of the probability density functions of total AGB error across the three regression approaches. The results are shown in Figure 15. It can be seen from the figure that, with the same model, equations developed using the first regression approach are the least robust (i.e., having largest ranges of error). Equations developed using the second regression approach are the most robust. Equations developed using the third regression approach has slightly larger ranges of error but they are more accurate than equations developed using the second approach for the first and the second input group.

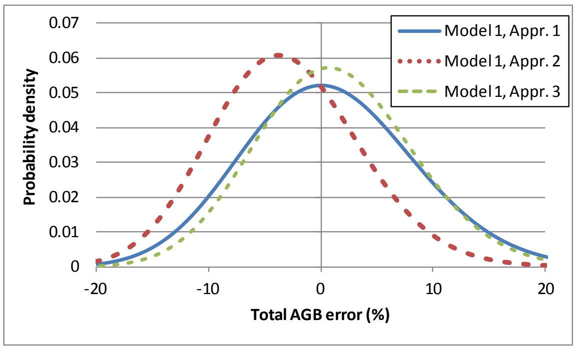
Based on the results of the comparison, we recommend to use (i) the equation derived from Model 1 using the third regression approach when D is the only input variable; (ii) the equation derived from Model 4 using the third regression approach when D and H are used as the input variables; (iii) the equation derived from Model 6 using the second regression approach when D and ρ are used as the input variables; and (iv) the equation derived from Model 8 using the second regression approach when all three parameters D, H and ρ are used as the input variables. Specifically, the following equations are recommended to apply:

$$AGB = 0.1142 \times D^{2.4451} \quad \text{(Eq. 6)}$$

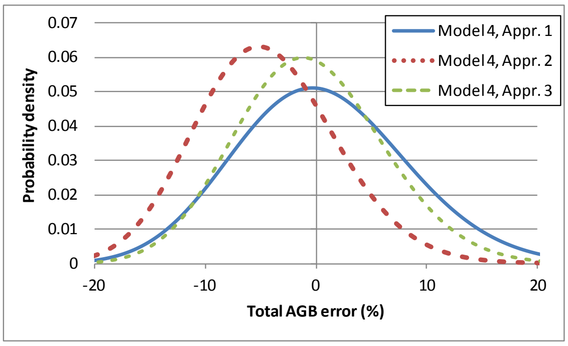
$$AGB = 0.0547 \times D^{2.1148} \times H^{0.6131} \quad \text{(Eq. 7)}$$

$$AGB = 0.2176 \times D^{2.3825} \times \rho^{0.7996} \quad \text{(Eq. 8)}$$

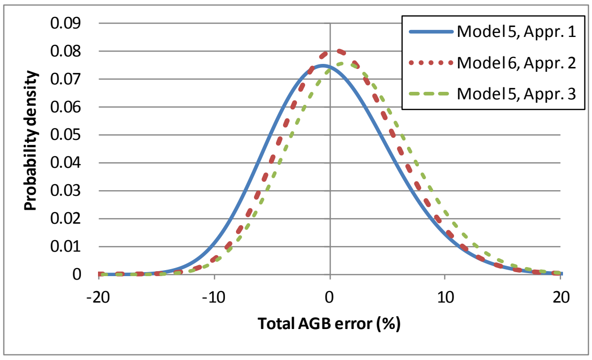
$$AGB = 0.1173 \times (D^2 H^{0.7} \rho)^{0.9898} \quad \text{(Eq. 9)}$$



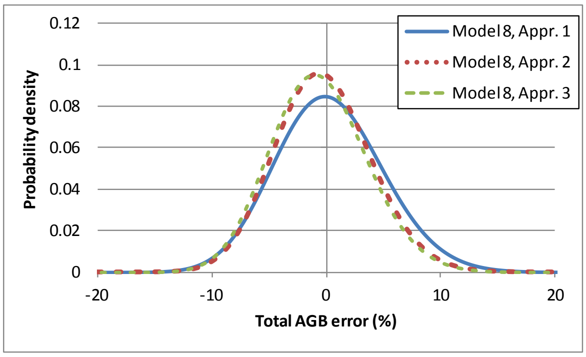
(a) Models that use only variable D



(b) Models that use only D and H



(b) Models that use only D and ρ



(d) Models that use all three input variables

Figure 15: Comparison of the models across three regression approaches for each group of inputs (evergreen broadleaf)

Note that the probability density functions of the total AGB error reported in this section are for equations that are derived from a random dataset of 143 (two thirds of 215) trees and predict the total AGB of a random and independent dataset of 72 trees (one third of 215). Normally, the ranges of error of the equations decrease with the size of the training dataset. The equations from 14 to 17 are derived from the whole dataset (i.e., all 215 trees) so they should have smaller ranges of error (i.e., more robust) than those reported in this section. The ranges of error of the equations also depend on the size of the testing dataset. Our previous analyses to develop volume equations indicate that with a given model, when the size of the testing dataset increases, the expected value (i.e., the mean) of the error is almost unchanged while the range of error is narrowed (unpublished data). If this holds true for biomass equations, then it can be safe to use the expected values and the ranges of error reported in this section for the equations from 6 to 9 above when predicting the total AGB of 72 or more trees. The expected values and the ranges of error for these equations are given in Table 20.

Table 20: Expected values and ranges of total AGB error for equations from 6 to 9 when predicting total AGB of 72 or more trees.

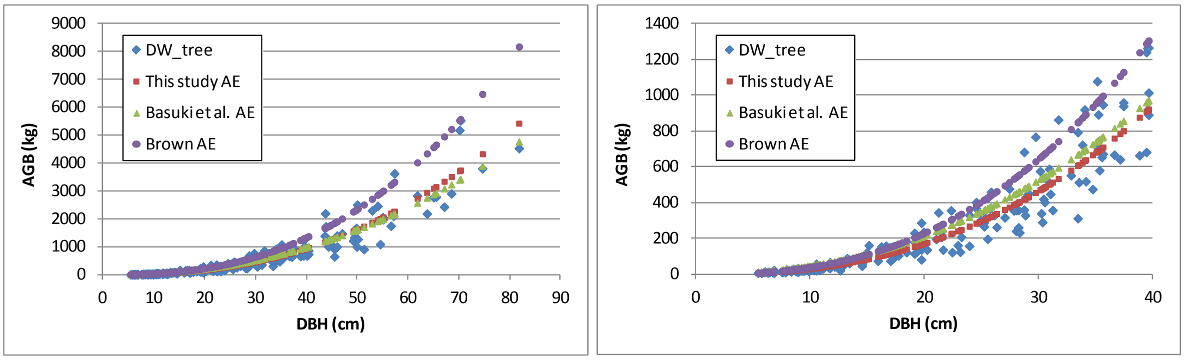
Eq. No.	Equation	Expected value of error (%)	Range of error (95% CL)
6	$AGB = 0.1142 \times D^{2.4451}$	1.2603	-11.85 ÷ 15.55

7	$AGB = 0.0547 \times D^{2.1148} \times H^{0.6131}$	-0.5614	-13.08 ÷ 13.21
8	$AGB = 0.2176 \times D^{2.3825} \times \rho^{0.7996}$	1.0463	-8.17 ÷ 11.46
9	$AGB = 0.1173 \times (D^2 H^{0.7} \rho)^{0.9898}$	-0.3002	-8.14 ÷ 8.24

3.3.3 Modeling of ABG for the main tree families and species

3.3.4 Comparison with generic models

We did a comparison of our Eq. (14) (which uses DBH as the only input variable) with other two equations. The first equation is: $AGB = \exp(-2.134 + 2.530 \times \ln(DBH))$, which is developed by Brown (1997) for all tropical moist forests. The second equation is $AGB = \exp((-1.201 + 2.196 \times \ln(DBH))$, which is developed by Basuki *et al.* (2009) for mixed species in tropical lowland Dipterocarp forests. The result is shown in Figure 16.



(a) For all trees (b) For trees having DBH < 40 cm

Figure 16: Comparison between the Model1 fitted AE and the Brown (1997) AE

It can be observed that the Brown AE seems to significantly over-estimate the AGB of trees in our dataset. Thus, it should be used with care when estimating forest biomass in Vietnam. The Basuki *et al.* equation, although closer to the equation developed in this Study, seems to under-estimate the AGB for large trees (Figure 13(a)) and over-estimate the AGB for trees having DBH < 40 cm (Figure 13(b)).

Next, we compared our developed Eq. 17 with the equation developed by Chave *et al.* (2005), which is $AGB = 0.0509 \times D^2 H\rho$. The result is shown in Figure 17. It can be seen from the figure that the Chave *et al.* AE tends to over-estimate the AGB of trees in our dataset.

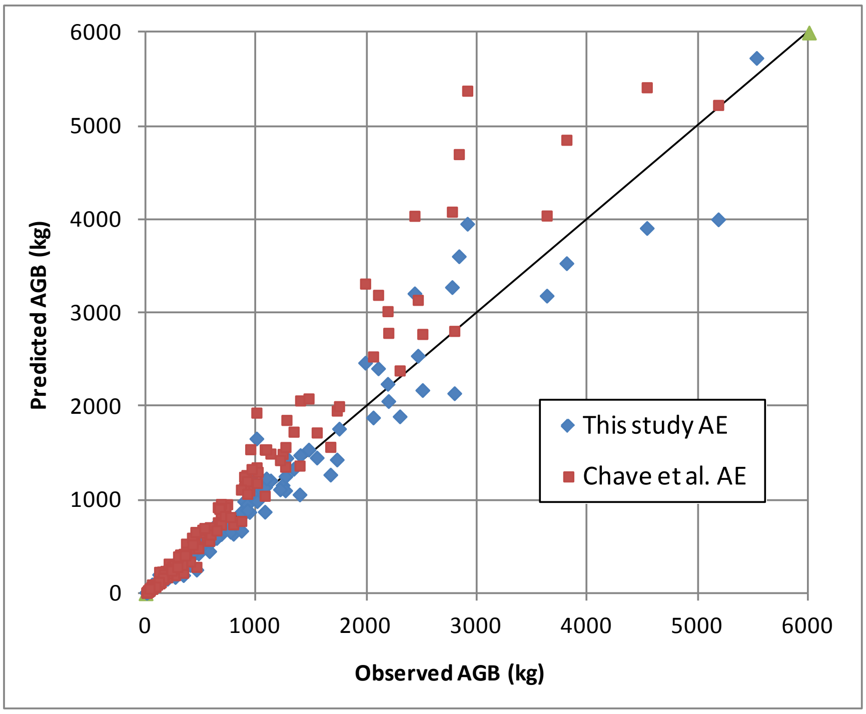


Figure 17: Comparison between Eq. 17 in this study and the Chave et al. (2005) AE (evergreen broadleaf dataset)

Finally, we used the current dataset to calculate the average deviation $\bar{S}$ (%) and the total AGB error S (%) for different equations, which are either developed in this study or previously developed. $\bar{S}$ is calculated using Equation 10 below:

$$\bar{S}(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{|\hat{Y}i - Yi|}{Yi} \qquad (10)$$

Where n is the number of sample trees; $\hat{Y}i$ and Yi are the predicted and measured AGB of the ith tree, respectively. The results are provided in Table 21.

Table 21: The standard deviation of different equations (evergreen broadleaf dataset)

No.	Equation	$\bar{S}$(%)	S(%)	Source
1	AGB = $0.1142 \times D^{2.4451}$	27.34	0.98	Eq. 6 from this study
2	AGB = $0.0547 \times D^{2.1148} \times H^{0.6131}$	25.76	-0.89	Eq. 7 from this study
3	AGB = $0.2176 \times D^{2.3825} \times \rho^{0.7996}$	15.38	0.92	Eq. 8 from this study
4	AGB = $0.1173 \times (D^2H^{0.7}\rho)^{0.9898}$	13.02	-0.42	Eq. 9 from this study
5	AGB = exp((-1.201 + 2.196×ln(D))	45.24	3.49	Basuki *et al.* (2009)
6	AGB = exp(-2.134 + 2.530×ln(D))	51.39	44.75	Brown (1997)
7	AGB = $0.0509 \times D^2H\rho$	25.76	25.55	Chave *et al.* (2005)

As can be seen, Eq. 9 from this study has the smallest $\bar{S}$ (13.02%), followed by Equations 8, 7 and 6, in that order. For the three previously developed equations, the Chave *et al.* AE performs the best. This is understandable as this AE uses all three input variables while the other two use only the variable D. The Basuki *et al.* AE, although looks quite similar to Eq. 6 in Figure 13(a), still have the $\bar{S}$ value of 45.24%. The Brown AE has the largest $\bar{S}$ (51.39%).

In terms of the total AGB error *S*, equations developed in this study have the lowest values and are all < 1%. The Basuki *et al.* AE over-estimates the total AGB of the current dataset by 3.49%. The Chave *et al.* AE and Brown AE over-estimate the total AGB by 25.55% and 44.75%, respectively.

3.4 Result 4: BEF (totalAGB/ABGstem)

The results of dry mass analysis of 215 sample trees are given in Table 22. In average, stems have the highest ratio and branches rank second. The coefficient of variation (CV, %) of the ratios is smallest in stems and highest in leaves.

Table 22: Ratio of dry to fresh biomass of evergreen broadleaf forests

Statistical values	Dry to fresh mass ratio		
	Stem	Branch	Leaf
Min	0.406	0.318	0.196
Max	0.691	0.623	0.494
Avg	0.544	0.479	0.347
Stdev	0.063	0.063	0.069
CV(%)	11.640	13.134	19.875

From the data of fresh biomass and the dry-to-fresh mass ratio, the dry biomass of each component of the trees is calculated using the formula (2) in Section 2 above. Data on species name, DBH, height, wood density, and total dry weight of these sample trees are given in Annex 3.

The fractions of dry biomass for each component of the trees are given in Figure 18. Fractions of dry biomass of stem, branches and leaves in our dataset are 82.6%, 15.5% and 1.9%, respectively.

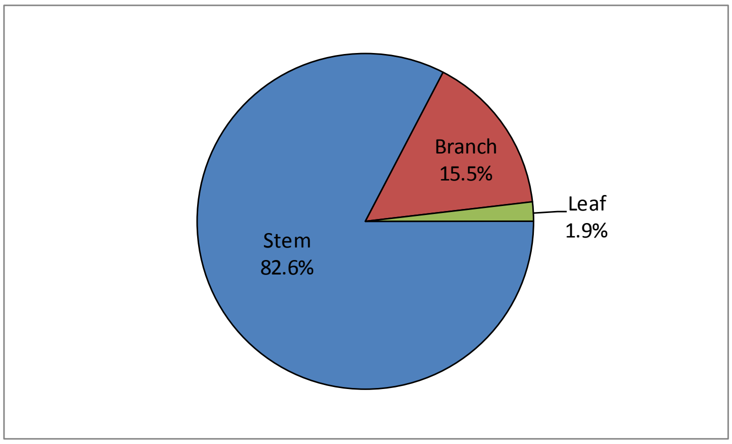


Figure 18: Fractions of dry biomass of each component of the tree

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

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

The result for the 215 trees sampled in evergreen broadleaved forest is a BEF average value of 1.238 ± 0.147. The minimal value is 1.020 and the maximal is 1.829.

4 RESULTS FOR BAMBOO (*INDOSASA ANGUSTATA*)

4.1 Result 1: forest and trees characteristics

4.1.1 Forest structure

N-D distribution

In the two *Indosasa angustata* sample plots LC-VB-02A and LC-VB-02B, ten sub-plots, each has a size of 10m x 10m, have been established and all live bamboos with DBH ≥ 2 cm in the sub-plots are measured. There are totally 458 bamboos in these 10 sub-plots so the estimated density of the *Indosasa angustata* forest is 4,580 bamboos/ha. The N-D distribution of these bamboos is shown in Figure 19. This is a one peak distribution which the peak is at the 10.0-11.9 cm DBH class.

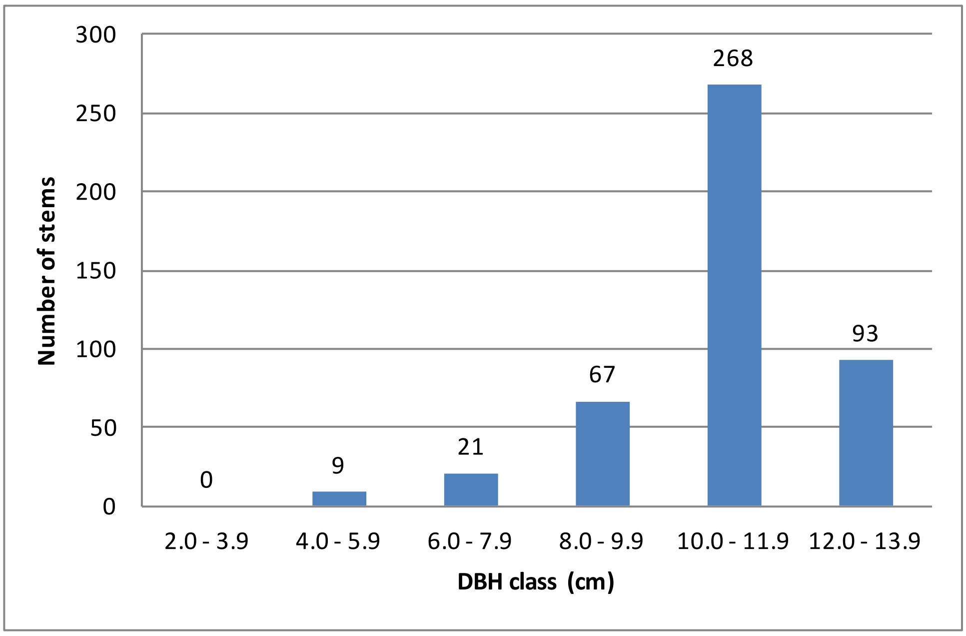


Figure 19: N-D distribution of the two *Indosasa angustata* sample plots

Proportion of age class

The proportion of age classes of the 458 bamboos is given in Figure 20. It can be seen that most of the bamboos (72.5%) are in the old age class. The medium-aged class ranks second (19.2%) and the young class only accounts for 8.3% of the total bamboos.

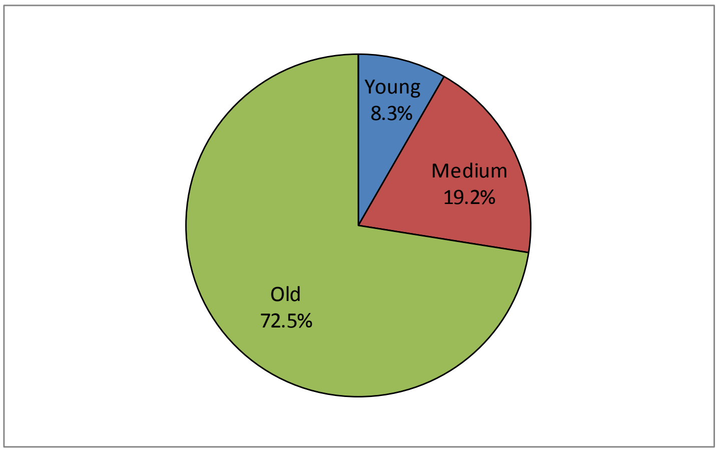


Figure 20: Proportion of age classes in two *Indosasa angustata* sample plots

4.1.2 Relation between H and diameter

70 bamboos are felled down for destructive biomass measurement. (Note that the destructive measurement of these two bamboo plots was conducted during the initial study, where the main objective is to develop the cost-norms for the second study. At that time, the target was to undertake the destructive measurement of 100 bamboos, but due to the under-estimation of the cost, we were able to undertake the destructive measurement of only 70 bamboos.)The D-H correlation function of the 70 felled bamboos in two sample plots VB-TN-01 and VB-TN-02 is shown in Figure 21. As can be observed, the correlation coefficient R^2 of the regression equation is not as high as compared the D-H correlation functions of evergreen broadleaf forests. This implies that we may need to include H in models to predict biomass of bamboo forests.

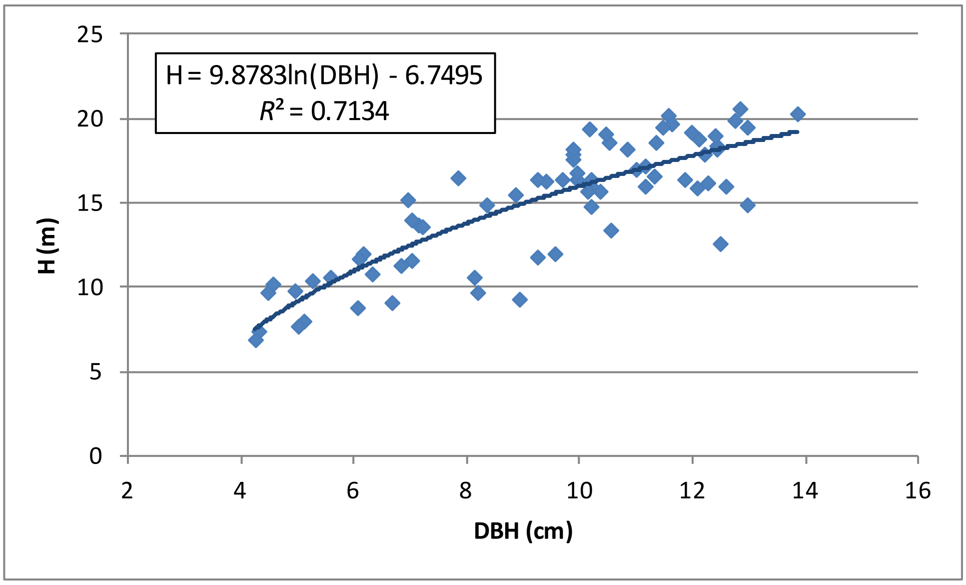


Figure 21: D-H correlation function of the felled bamboos in *Indosasa angustata* sample plots

4.1.3 Biomass of sample trees

Totally, biomass data of 70 sample bamboos are collected. The numbers of bamboos by DBH classes and age classes are given in Table 23. Data on species name, DBH, height, age class, and dry weight of each component of these sample bamboos are given in Annex 4.

Table 23: Numbers of sample bamboos by DBH classes and age classes

DBH Class	Age class			Total
	Old	Medium	Young	
4.0 - 5.9 cm	3	3	3	**9**
6.0 - 7.9 cm	5	4	3	**12**
8.0 - 9.9 cm	6	6	3	**15**
10.0 - 11.9 cm	9	7	3	**19**
12.0 - 13.9 cm	8	4	3	**15**
Total	**31**	**24**	**15**	**70**

Among the 70 bamboos sampled for fresh biomass, only 50 of them are sampled for dry mass analysis. The results of dry mass analysis are given in Table 24. It can be seen that the ratios of the young class are lowest. Between the old and medium age classes, the ratios of the stem and leaf are approximately equal to each others. The ratio of the branch part, however, is clearly higher in the old class.

Table 24: Ratio of dry biomass to fresh biomass of different bamboo components

Age class	Bamboo part	*N*	Min	Max	Avg	Stdev	CV(%)
Old	Stem	25	0.286	0.589	0.437	0.093	21.246
	Branch	25	0.342	0.601	0.469	0.067	14.360
	Leaf	25	0.331	0.453	0.398	0.031	7.720
Medium	Stem	16	0.265	0.571	0.445	0.090	20.267
	Branch	16	0.279	0.487	0.409	0.053	12.875
	Leaf	16	0.338	0.442	0.397	0.029	7.206
Young	Stem	9	0.247	0.698	0.363	0.138	38.052
	Branch	9	0.239	0.408	0.323	0.056	17.414
	Leaf	9	0.278	0.383	0.341	0.031	9.165
All	Stem	50	0.247	0.698	0.426	0.104	24.312
	Branch	50	0.239	0.601	0.423	0.081	19.121
	Leaf	50	0.278	0.453	0.387	0.037	9.504

4.2 Result 2: Modeling of the stem volume

The stem volume has not been measured during the field work so no model has been developed.

4.3 Result 3: Modeling of Aboveground biomass

4.3.1 Modeling of total aboveground biomass

Model fitting

First, regression analyses using the first approach for the 4 statistical models (Models 1-4 in Section 2.5) are undertaken using the procedure NLIN in the SAS software. The analyzed results are given in Table 25.

Table 25: Results of regression analyses using the first approach (*Indosasa angustata*)

No	Model	*a**	*b**	*c**	$\bar{R}^2$	SSE	Pr > F
1	$B = aD^b$	0.2243	1.8473		0.7577	1061.324	<.0001
2	$B = a(D^2H)^b$	0.1223	0.6607		0.7480	1103.636	<.0001
3	$B = a(D^2H^{0.7})^b$	0.1337	0.7305		0.7561	1068.346	<.0001
4	$B = aD^bH^c$	0.1698	1.6895	0.2331	0.7584	1042.608	<.0001

* All coefficients are significant at $p < 0.001$.

All equations have quite high $\bar{R}^2$ value, indicating that they can all be used to estimate forest biomass. Equations derived from Models 2 and 3, although using both variables D and H, have lower $\bar{R}^2$ as compared to the equation derived from Model 1, which uses only variable D. This indicates that the D^2H and $D^2H^{0.7}$ forms are not suitable for bamboo forest. The equation derived from Model 4 has the highest $\bar{R}^2$.

Next, regression analyses using the second approach are performed using the procedure NLIN in the SAS software. The analyzed results are provided in Table 26.

Table 26: Results of regression analyses using the second approach (*Indosasa angustata*)

No	Model	*a**	*b**	*c**	$\bar{R}^2$	SSE	Pr > F
1	$B = aD^b$	0.2117	1.8568		0.8453	4.426	<.0001
2	$B = a(D^2H)^b$	0.1136	0.6657		0.8468	4.384	<.0001
3	$B = a(D^2H^{0.7})^b$	0.1287	0.7310		0.8497	4.274	<.0001
4	$B = aD^bH^c$	0.1477	1.5885	0.3558	0.8506	4.237	<.0001

* All coefficients are significant at $p < 0.001$.

It can be observed that, with the same model, the coefficients estimated using the second approach are quite different from those estimated using the first approach. The order of the models (ranked by $\bar{R}^2$) using the second approach is similar to that using the first approach. There is a smal difference. Models 2 and 3 now has higher $\bar{R}^2$ as compared to Model 1.

Finally, regression analyses using the third approach are done by the procedure NLP in the SAS software. The analyzed results are given in Table 27.

Table 27: Results of regression analyses using the third approach (*Indosasa angustata*)

No	Model	*a**	*b**	*c**	Log*L*	AICc
1	$B = aD^b$	0.2184	1.8567		-179.056	362.291

No	Model	*a**	*b**	*c**	Log*L*	AICc
2	$B = a(D^2H)^b$	0.1194	0.6617		-177.436	359.050
3	$B = a(D^2H^{0.7})^b$	0.1358	0.7265		-176.865	357.910
4	$B = aD^bH^c$	0.1453	1.5171	0.4313	-176.792	359.948

* All coefficients are significant at $p < 0.001$.

It can be seen from the table that the values of the coefficients estimated using the third approach are quite close to those estimated using the second approach. The order of the models ranked by AICc is the same with the order ranked by $\bar{R}^2$ of the second regression approach. Among the four models, Model 4 has the lowest (i.e., best) AICc.

Cross validation and error assessment

To avoid over-fitting of the models, we carried out cross validation tests as described in Section 2.7. Table 28 shows the properties of the approximated probability density functions of the total AGB error for every equations developed using the first approach.

Table 28: Properties of the probability density functions of the total AGB error (%) for the equations developed using the first regression approach (*Indosasa angustata*)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0127	0.0873	0.0033	0.564	0.262	-0.339	0.0580	0.9997	-12.17	15.02	27.19
2	0.0140	0.0980	0.0039	0.627	0.282	-0.403	0.0571	0.9997	-12.23	15.45	27.68
3	0.0138	0.0950	0.0034	0.574	0.245	-0.409	0.0580	0.9997	-12.11	15.13	27.24
4	0.0126	0.0871	0.0052	0.716	0.412	-0.191	0.0576	0.9997	-12.13	15.28	27.41

In this table, the means (or expected values) of error indicate the accuracy while the ranges of error show the robustness of the models. All models tend to over-estimate the total AGB by about 0.6-0.7%. Model 1, although using only variable D, is the most accurate and robust. However, the differences between the models are very small and may be not statistically significant. The probability density functions of total AGB error for these models are shown in Figure 22.

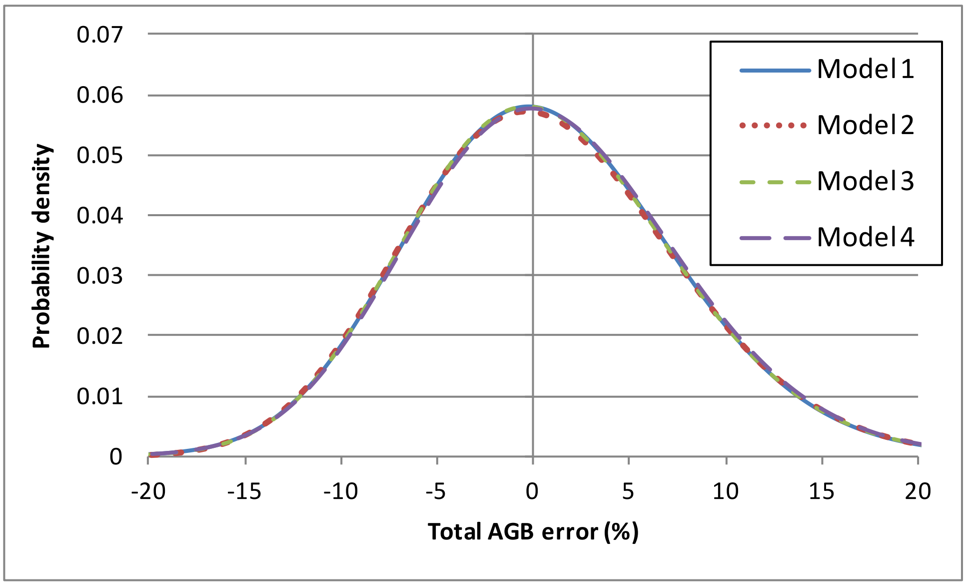


Figure 22: Probability density functions of the total AGB error (%) for equations developed by the first regression approach (*Indosasa angustata*)

Next, the cross validation test is performed for equations derived using the second regression approach. The results are provided in Table 29.

Table 29: Properties of the probability density functions of the total AGB error (%) for the equations developed using the second regression approach (*Indosasa angustata)*

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0121	0.0825	-0.0373	-2.741	-3.012	-3.549	0.0612	0.9997	-14.85	10.91	25.76
2	0.0120	0.0848	-0.0380	-2.815	-3.103	-3.678	0.0589	0.9996	-15.39	11.4	26.79
3	0.0120	0.0829	-0.0369	-2.745	-3.022	-3.573	0.0600	0.9997	-15.09	11.17	26.26
4	0.0124	0.0860	-0.0363	-2.575	-2.862	-3.433	0.0601	0.9996	-14.88	11.36	26.24

It can be observed that equations developed using the second regression approach tend to under-estimate the total AGB by about 2.6-2.8%. Once again, Model 1 seems to outperform other models on the robustness aspect. The probability density functions of the four models are shown in Figure 23.

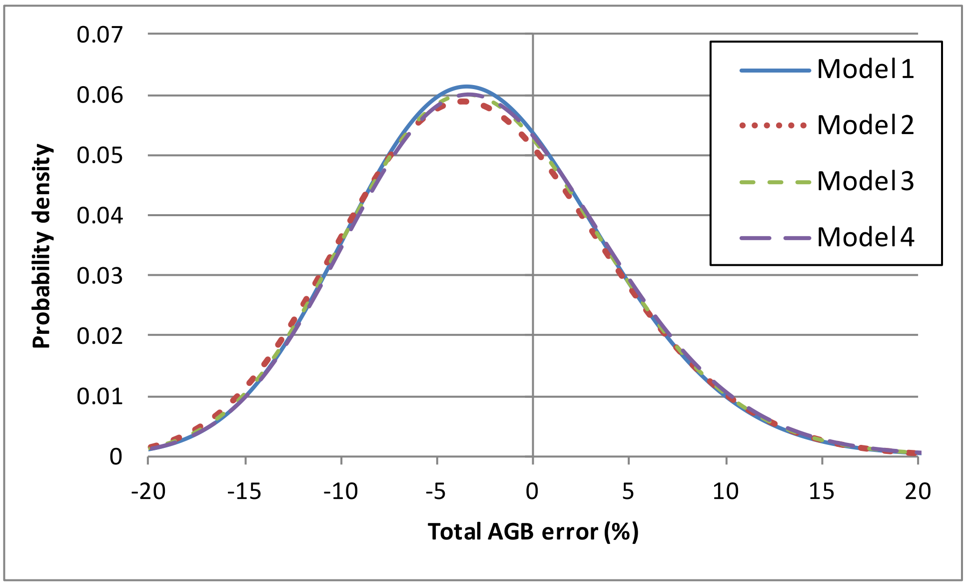


Figure 23: Probability density functions of the total AGB error (%) for some selected equations developed by the second regression approach (*Indosasa angustata*)

Finally, the cross validation test is performed for equations developed using the third regression approach and the results are provided in Table 30.

Table 30: Properties of the probability density functions of the total AGB error (%) for the equations developed by the third regression approach (*Indosasa angustata*)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0131	0.0898	-0.0044	-0.031	-0.338	-0.948	0.0587	0.9997	-12.59	14.28	26.87
2	0.0149	0.1076	-0.0231	-1.148	-1.528	-2.280	0.0570	0.9997	-13.96	13.82	27.78
3	0.0144	0.1011	-0.0137	-0.592	-0.944	-1.641	0.0579	0.9997	-13.26	14.08	27.34
4	0.0142	0.1000	-0.0125	-0.525	-0.872	-1.562	0.0578	0.9997	-13.22	14.14	27.36

It can be observed that the equation derived from Model 1 is the most accurate (the expected mean error is -0.03%) and robust. The probability density functions of the total AGB error for these equations are shown in Figure 24.

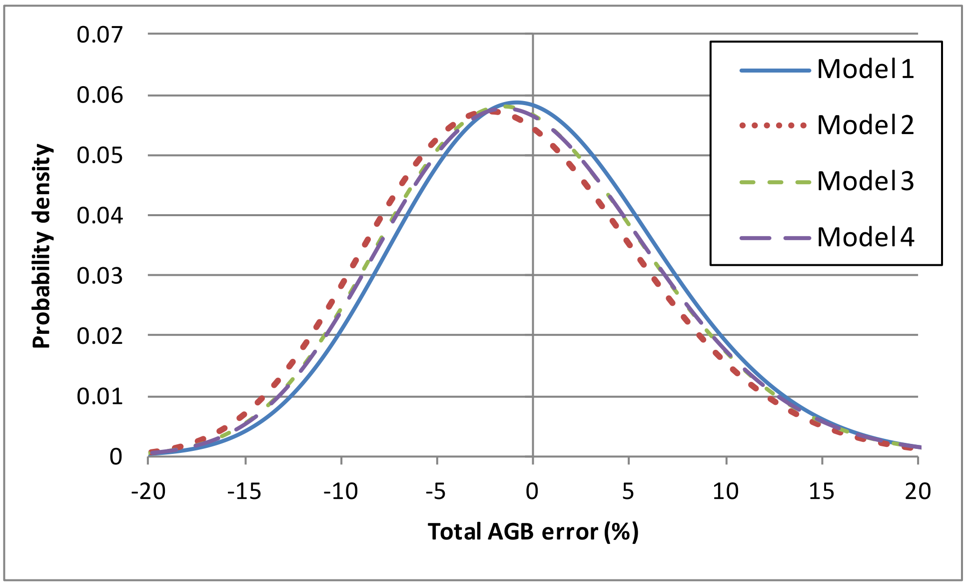


Figure 24: Probability density functions of the total AGB error (%) for equations developed using the third regression approach (*Indosasa angustata*)

Based on the above results, it can be concluded that the inclusion of H does not improve the accuracy nor the robustness of biomass estimation for *Indosasa angustata* forest. In order to find the best equations, we did a comparison of the probability density functions of total AGB error across the equations derived from Model 1 using the three regression approaches. The results are shown in Figure 25.

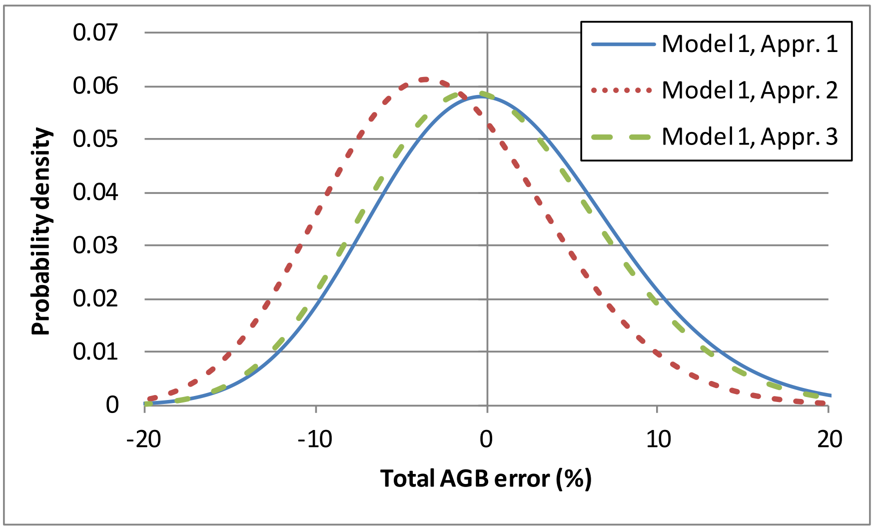


Figure 25: Comparison of equations derived from Model 1 across three regression approaches (*Indosasa angustata*)

It can be seen from the figure that, with the same model, the equation developed using the second regression approach is the most robust but least accurate. The equation developed using the third regression approach, although having slightly larger ranges of error, is the most accurate. Therefore, it is recommended to choose the equation developed using the third approach, which is:

$$AGB = 0.2184 \times D^{1.8517} \quad (11)$$

With similar arguments with the ones in Section 4.1, it can be safe to use the expected value and the range of error reported in this section for Eq. 11 above when predicting the total AGB of 23 (⅓ of 70 trees) or more trees. The expected value and range of error are given in Table 31.

Table 31: Expected value and range of total AGB error for Eq. 11 when predicting total AGB of 23 or more trees.

Eq. No.	Equation	Expected value of error (%)	Range of error (95% CL)
11	$AGB = 0.2184 \times D^{1.8517}$	-0.031	-12.59 ÷ 14.28

4.3.2 Development of allometric equations for each age class

In order to see whether the development of allometric equations specified for each age group of the bamboos can improve the biomass prediction, we performed an experiment to generate the probability density functions for Model 1 using the third regression approach (since it has been proved to be the best for *Indosasa angustata* bamboos) for each age class. The results are provided in Table 32.

Table 32: Properties of the probability density functions of the total AGB error (%) for the equation developed for each age class using Model 1 and the third regression approach

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0102	0.0685	-0.0101	-0.752	-0.981	-1.435	0.0601	0.9988	-13.18	12.97	26.15

It can be seen from the table that when developing equations specified to each age class of bamboos, the range of error for Model 1 has been narrowed from 26.87% (see Table 30) to 26.15%. This means that the robustness of the prediction has been improved. However, on the accuracy aspect, the approach that use equations specified to each age class is less accurate, with the expected value for Model 1 is -0.75% (as compared to -0.03% when using a general equation for all age classes). There is a tradeoff between accuracy and robustness when using equations developed specifically for each bamboo).

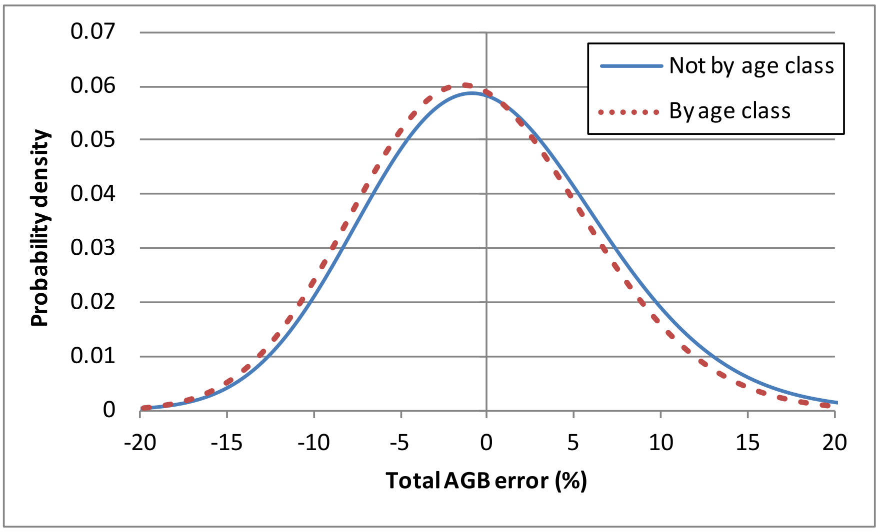


Figure 26: Comparison of two approaches: (i) using one equation for all age classes and (ii) using three equations specified for each age class (Model 1, third approach)

The age-class specific AEs relating the AGB and DBH (developed using Model 1 and the third regression approach) are given in Table 33 and Figure 27. It can be observed from the figure that with the same DBH, the total AGB of bamboos tends to be highest in the medium-aged class, followed by the old class (the difference, however, is quite small). The young class has the lowest AGB.

Table 33: Results of regression analyses (using Model 1 and the third regression approach) for the bamboo dataset divided by each age class

Age class	Parameter *a*				Parameter *b*			
	Estimate	Std. err.	t value	Pr > |t|	Estimate	Std. err.	t value	Pr > |t|
All classes	0.218	0.041	5.357	<0.001	1.857	0.085	21.772	<0.001
Old	0.185	0.060	3.063	<0.005	1.932	0.146	13.238	<0.001
Medium	0.304	0.059	5.118	<0.001	1.759	0.104	16.945	<0.001
Young	0.218	0.074	2.946	<0.05	1.745	0.160	10.874	<0.001

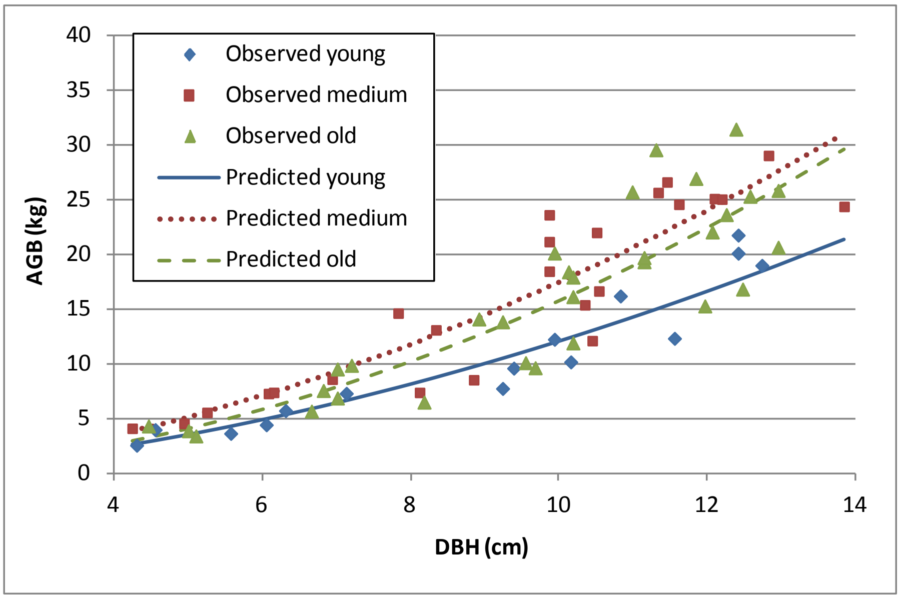


Figure 27: Allometric equations relating the AGB (kg) with DBH (cm) for each age class

4.3.3 Modeling per tree compartments

Regression analyses using Model 1 and the third approach were undertaken to develop the AEs for calculating the stem, branch and leaf dry biomass of the bamboos. Cross validation tests are also conducted to estimate the means and ranges of error for these equations. The results are given in Table 34 and Figures 30 – 32 below. The results show that the allometric equations for estimating branch and leaf biomass from DBH have very large ranges of error and should be used with care in practice. An attempt to develop age-class-specific AEs for branch and leaf has been made but no clear improvement on the accuracy as well as robustness of prediction was observed (data not shown).

Table 34: Results of regression analyses using Model 1 and the third regression approach for each part of bamboos

Part	Parameter *a*				Parameter *b*				Error mean (%)	Range of error (%)
	Estimate	Std. err.	t value	Pr > |t|	Estimate	Std. err.	t value	Pr > |t|		
Stem	0.091	2.165	6.087	<0.001	2.165	0.075	28.689	<0.001	0.667	-12.43 ÷ 15.48
Branch	0.117	0.038	3.086	<0.005	0.973	0.156	6.243	<0.001	-0.147	-23.01 ÷ 28.13
Leaf	0.335	0.146	2.295	<0.05	0.568	0.203	2.801	<0.01	-0.035	-22.71 ÷ 28.91

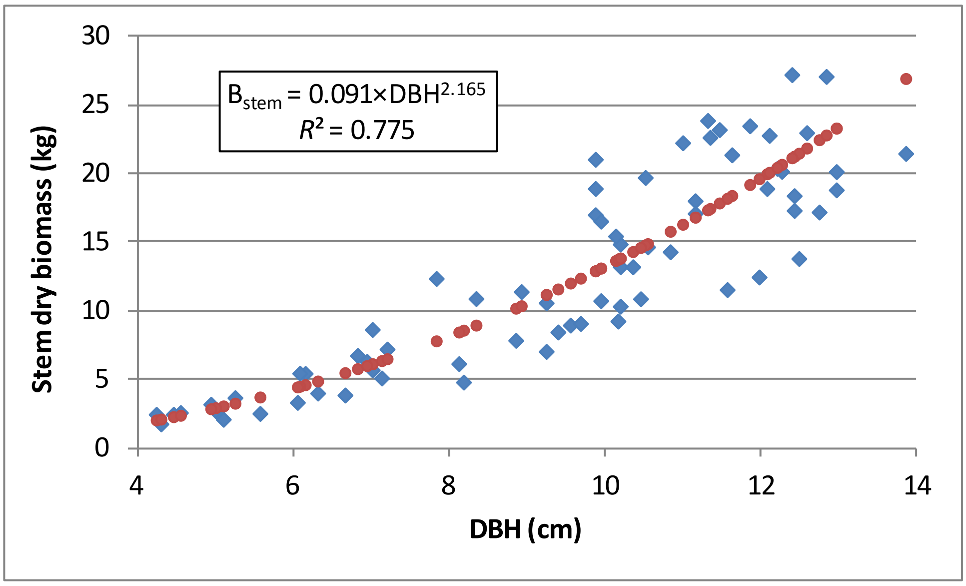


Figure 28: Allometric equation relating the stem dry biomass (kg) with DBH (cm) for all age classes

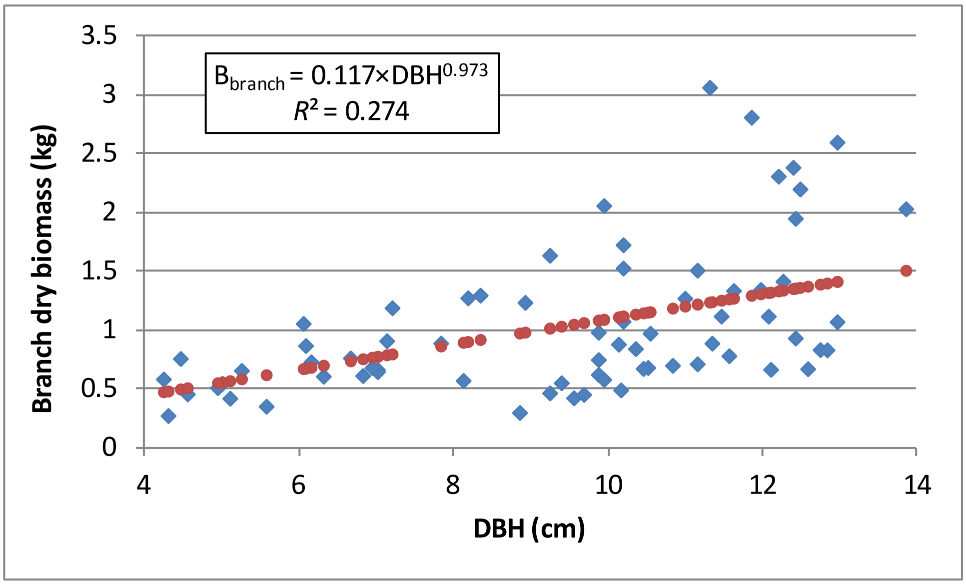


Figure 29: Allometric equation relating the branch dry biomass (kg) with DBH (cm) for all age classes

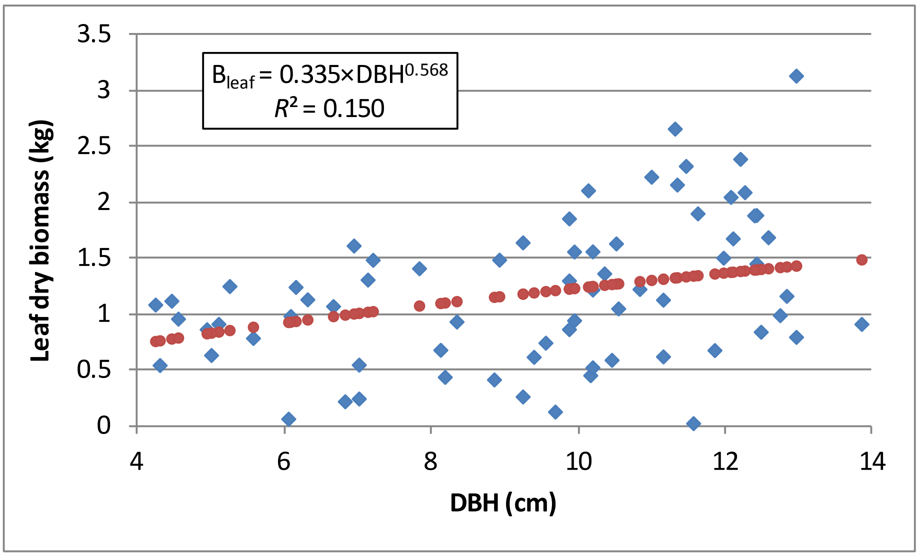


Figure 30: Allometric equation relating the leaf dry biomass (kg) with DBH (cm) for all age classes

5 RESULTS FOR BAMBOO (*B. CHIROSTACHYOIDES*)

5.1 Result 1: forest and trees characteristics

5.1.1 Forest structure

N-D distribution

In the *B. chirostachyoides* sample plot BK-CM-01, four sub-plots, each has a size of 20m x 20m, have been established and all live bamboos with DBH ≥ 2 cm in the sub-plots are measured. There are totally 2,209 bamboos in these 4 sub-plots. Thus, the estimated density of the B. chirostachyoides forest is 13,800 bamboos/ha. The N-D distribution of these bamboos is shown in Figure 31. This is a one peak distribution which the peak is at the 3.0-3.9 cm DBH class.

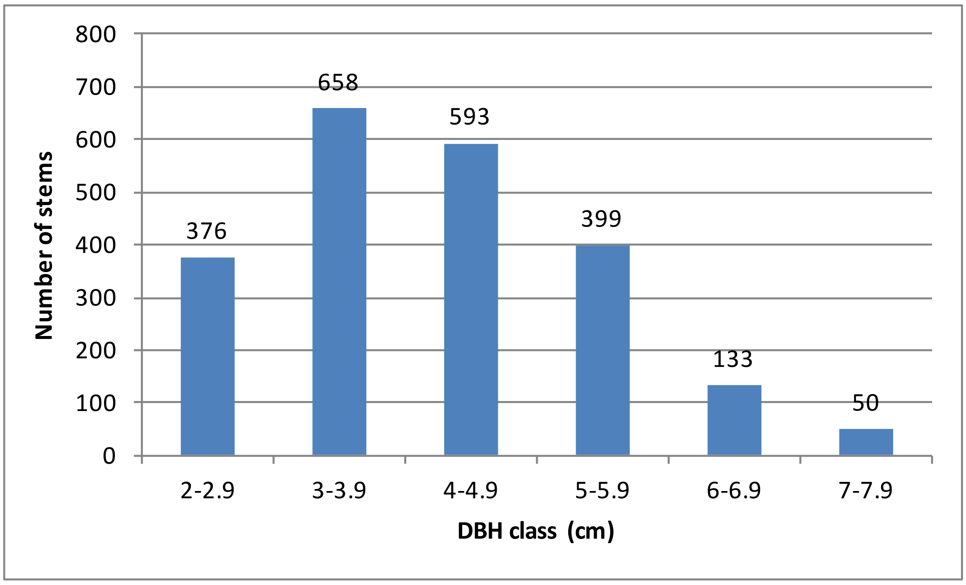


Figure 31: N-D distribution of the *B. chirostachyoides* sample plot

Proportion of age class

The proportion of age classes of the 2,209 bamboos is given in Figure 32. It can be seen that about half (49.7%) of the bamboos are in the medium-aged class. Old and young classes each accounts for approximately one fourth of the total bamboos.

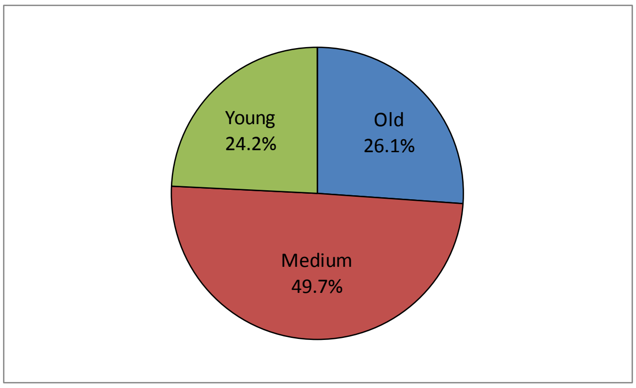


Figure 32: Proportion of age classes in the *B. chirostachyoides* sample plot

5.1.2 D-H relationship

120 bamboos are felled down for destructive biomass measurement. The D-H correlation function of the 120 felled bamboos in the sample plot BK-CM-01 is shown in Figure 33. As can be seen, the correlation coefficient R^2 of the regression equation for *B. chirostachyoides* is not so high. This implies that we may need to include H in models to predict biomass of *B. chirostachyoides* forests.

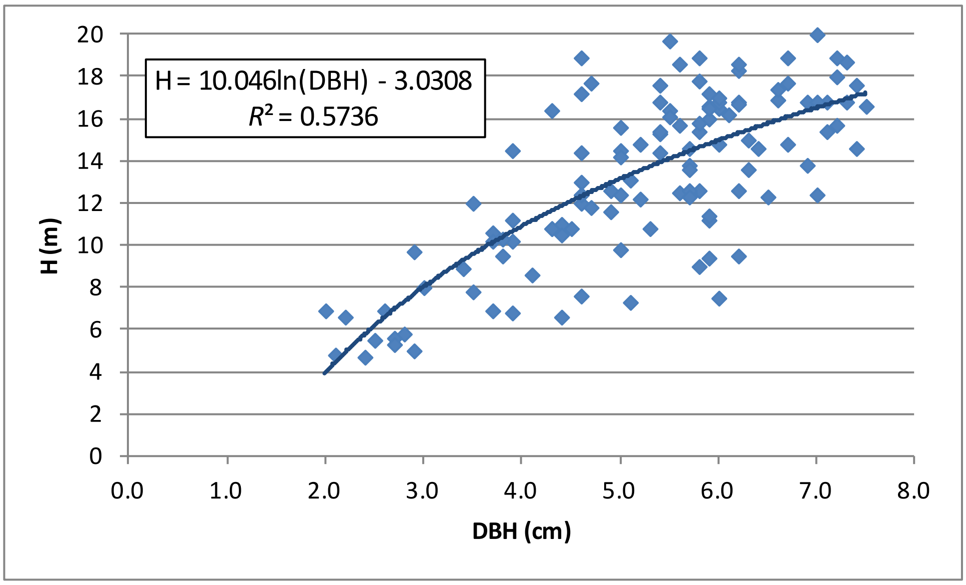


Figure 33: D-H correlation function of the felled bamboos in the *B. chirostachyoides* sample plot

5.1.3 Biomass of sample trees

Totally, biomass data of 120 sample bamboos are collected. The numbers of bamboos by DBH classes and age classes are given in Table 35. Data on species name, DBH, height, age class, and dry weight of each component of these sample bamboos are given in Annex 5.

Table 35: Numbers of sample bamboos by DBH classes and age classes

DBH Class	Age class			Total
	Old	Medium	Young	
2.0 – 3.9 cm	3	5	3	**11**
3.0 – 4.9 cm	3	7	3	**13**
4.0 – 4.9 cm	4	9	7	**20**
5.0 – 5.9 cm	12	19	9	**40**
6.0 – 6.9 cm	10	8	5	**23**
7.0 – 7.9 cm	3	7	3	**13**
Total	**35**	**55**	**30**	**120**

Among the 120 bamboos sampled for fresh biomass, only 70 of them are sampled for dry mass analysis. However, sub-samples of one sample bamboo have been lost, so the final dataset contains sub-sample data of only 69 sample trees. The results of dry mass analysis are given in Table 36. It can be seen that the ratios of the old class are highest, followed by the medium-aged class (except for the ratio of the branch part, where the ratio of medium-age class is lower than that of the young class). For the 51 trees that were not sampled for dry mass analysis, their dry to fresh biomass ratios are taken from the averages of each age class.

Table 36: Ratio of dry to fresh biomass of different bamboo components

Age class	Bamboo part	N	Min	Max	Avg	Stdev	CV(%)
Old	Stem	18	0.439	0.653	0.586	0.047	8.076
	Branch	18	0.441	0.646	0.580	0.060	10.414
	Leaf	18	0.371	0.524	0.455	0.051	11.237
Medium	Stem	34	0.433	0.644	0.564	0.062	11.001
	Branch	34	0.415	0.646	0.542	0.072	13.249
	Leaf	34	0.325	0.516	0.430	0.053	12.232
Young	Stem	17	0.413	0.658	0.555	0.066	11.950
	Branch	17	0.448	0.643	0.558	0.064	11.456
	Leaf	17	0.311	0.521	0.426	0.070	16.328
All	Stem	69	0.413	0.658	0.568	0.060	10.571
	Branch	69	0.415	0.646	0.556	0.068	12.243
	Leaf	69	0.311	0.524	0.435	0.057	13.144

5.2 Result 2: Modeling of the stem volume

The volume of the bamboo trees has not been measured.

5.3 Result 3: Modeling of Aboveground biomass

5.3.1 Total Aboveground biomass

Model fitting

First, regression analyses using the first approach for the 4 statistical models (Models 1-4 in Section 2.5) are undertaken using the procedure NLIN in the SAS software. The analyzed results are given in Table 37.

Table 37: Results of regression analyses using the first approach (*B. chirostachyoides*)

No	Model	*a**	*b**	*c**	$\bar{R}^2$	SSE	Pr > F
1	$B = aD^b$	0.4167	1.56835		0.9195	46.12	<.0001
2	$B = a(D^2H)^b$	0.2345	0.53863		0.9205	46.01	<.0001
3	$B = a(D^2H^{0.7})^b$	0.2512	0.60634		0.9349	37.75	<.0001
4	$B = aD^bH^c$	0.2883	1.36494	0.2729	0.9409	33.96	<.0001

* All coefficients are significant at p < 0.001.

All equations have high $\bar{R}^2$ value. Thus they can all be used to estimate forest biomass. Equations derived from Models 2, 3 and 4, which use both variables D and H, have higher $\bar{R}^2$ as compared to the equation derived from Model 1, suggesting that the variable H can contribute to the improvement of biomass estimation for *B. chirostachyoides* forest. Among those three equations, the equation derived from Model 4 has the highest $\bar{R}^2$.

Next, regression analyses using the second approach are performed using the procedure NLIN in the SAS software. The analyzed results are provided in Table 38.

Table 38: Results of regression analyses using the second approach (*B. chirostachyoides*)

No	Model	*a**	*b**	*c**	$\bar{R}^2$	SSE	Pr > F
1	$B = aD^b$	0.5590	1.3929		0.9312	1.503	<.0001
2	$B = a(D^2H)^b$	0.3836	0.4563		0.9166	1.822	<.0001
3	$B = a(D^2H^{0.7})^b$	0.4061	0.5141		0.9291	1.548	<.0001
4	$B = aD^bH^c$	0.4711	1.2327	0.1702	0.9380	1.343	<.0001

* All coefficients are significant at p < 0.001.

It can be observed that, the order of the models (ranked by $\bar{R}^2$) using the second approach is quite different from that using the first approach. Model 1 now has higher $\bar{R}^2$ than Models 1 and 2. Model 4 still has the highest $\bar{R}^2$ value.

Finally, regression analyses using the third approach are done by the procedure NLP in the SAS software. The analyzed results are given in Table 39.

Table 39: Results of regression analyses using the third approach (*B. chirostachyoides*)

No	Model	*a**	*b**	*c**	Log*L*	AICc
1	$B = aD^b$	0.5043	1.4587		-106.51	217.12
2	$B = a(D^2H)^b$	0.2512	0.5274		-112.38	228.87
3	$B = a(D^2H^{0.7})^b$	0.2621	0.5985		-100.70	205.50
4	$B = aD^bH^c$	0.3153	1.3450	0.2528	-93.90	194.00

* All coefficients are significant at p < 0.001.

It can be seen from the table that among the four models, Model 2 has the highest (i.e., the worst) AICc, followed by Model 1 and Model 3, in that order. Model 4 has the lowest (i.e., the best) AICc.

Cross validation and error assessment

To avoid over-fitting of the models, we carried out cross validation tests as described in Section 2.7. Table 40 shows the properties of the approximated probability density functions of the total AGB error for every equations developed using the first approach.

Table 40: Properties of the probability density functions of the total AGB error (%) for the equations developed using the first regression approach (*B. chirostachyoides*)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0126	0.0268	-0.0037	-0.267	-0.296	-0.353	0.1880	0.9999	-4.35	3.98	8.33
2	0.0142	0.0303	-0.0074	-0.490	-0.522	-0.586	0.1882	1.0000	-4.56	3.76	8.32
3	0.0151	0.0292	-0.0076	-0.473	-0.501	-0.557	0.2084	1.0000	-4.15	3.36	7.51
4	0.0148	0.0273	-0.0064	-0.406	-0.431	-0.481	0.2176	1.0000	-3.93	3.26	7.19

In this table, the means (or expected values) of error indicate the accuracy while the ranges of error (95% Confidence Interval) show the robustness of the models. It can be observed that equations developed using the first regression approach tends to slightly under-estimate the total AGB. Model 1 is the most accurate but least robust as it uses only the input variable D. Among the three models that use both variables D and H, Model 4 is the most accuate and robust. The probability density functions of total AGB error for these models are shown in Figure 34.

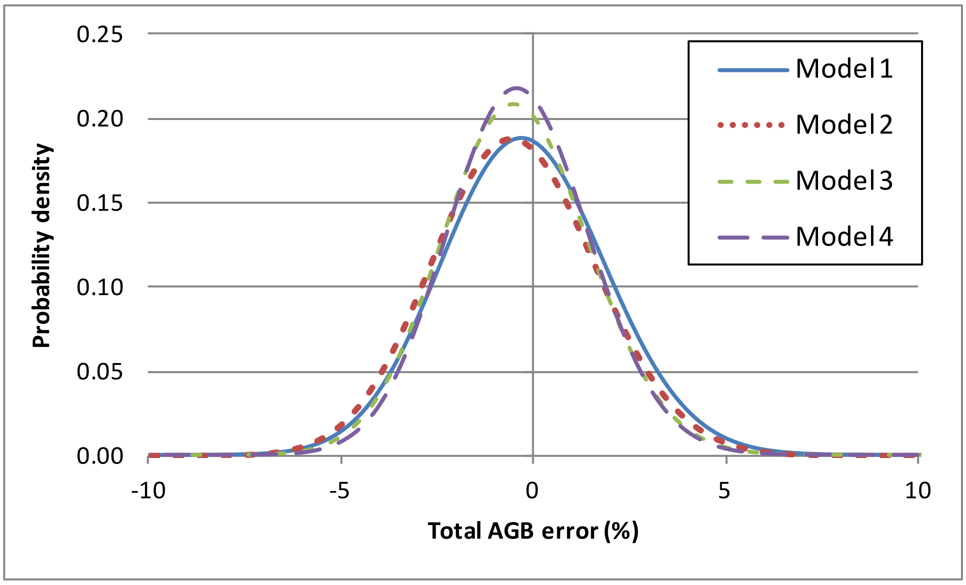


Figure 34: Probability density functions of the total AGB error (%) for equations developed by the first regression approach (*B. chirostachyoides*)

Next, the cross validation test is performed for equations derived using the second regression approach. The results are provided in Table 41.

Table 41: Properties of the probability density functions of the total AGB error (%) for the equations developed using the second regression approach (*B. chirostachyoides*)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range

1	0.0139	0.0312	-0.0143	-0.982	-1.017	-1.085	0.1811	1.0000	-5.21	3.44	8.65
2	0.0173	0.0406	-0.0209	-1.147	-1.193	-1.286	0.1742	1.0000	-5.51	3.48	8.99
3	0.0177	0.0382	-0.0197	-1.061	-1.102	-1.182	0.1892	1.0000	-5.09	3.19	8.28
4	0.0161	0.0330	-0.0157	-0.935	-0.969	-1.036	0.1972	1.0000	-4.81	3.13	7.94

It can be observed that all models tend to under-estimate the total AGB by about 1%. Model 1, although using only variable D, is more robust than Model 2, which uses both variables D and H. This indicates that the form D^2H is not suitable for *B. chirostachyoides* forest. Model 4 is the most accurate and robust but the differences between Model 4 and Model 1 are not so large. The probability density functions of the four models are shown in Figure 35.

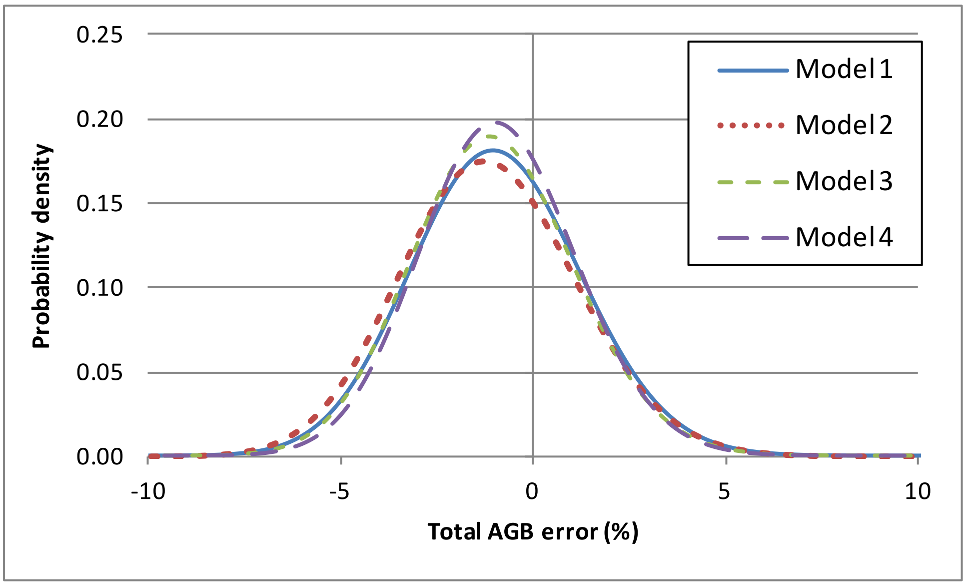


Figure 35: Probability density functions of the total AGB error (%) for some selected equations developed by the second regression approach (*B. chirostachyoides*)

Finally, the cross validation test is performed for equations developed using the third regression approach and the results are provided in Table 42.

Table 42: Properties of the probability density functions of the total AGB error (%) for the equations developed by the third regression approach (*B. chirostachyoides*)

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0093	0.0205	-0.0011	-0.096	-0.119	-0.164	0.1814	1.0000	-4.34	4.28	8.62
2	0.0132	0.0287	-0.0077	-0.550	-0.581	-0.644	0.1844	1.0000	-4.71	3.78	8.49
3	0.0134	0.0260	-0.0062	-0.438	-0.463	-0.513	0.2069	1.0000	-4.15	3.42	7.57
4	0.0111	0.0204	-0.0027	-0.229	-0.247	-0.285	0.2169	1.0000	-3.78	3.43	7.21

The equation derived from Model 1 is very accurate. The expected value of error is only -0.096%. However, its robustness is the least. Among the three models that use both variables D and H, Model 4 is the most accurate and robust. The probability density functions of the total AGB error for these equations are shown in Figure 36.

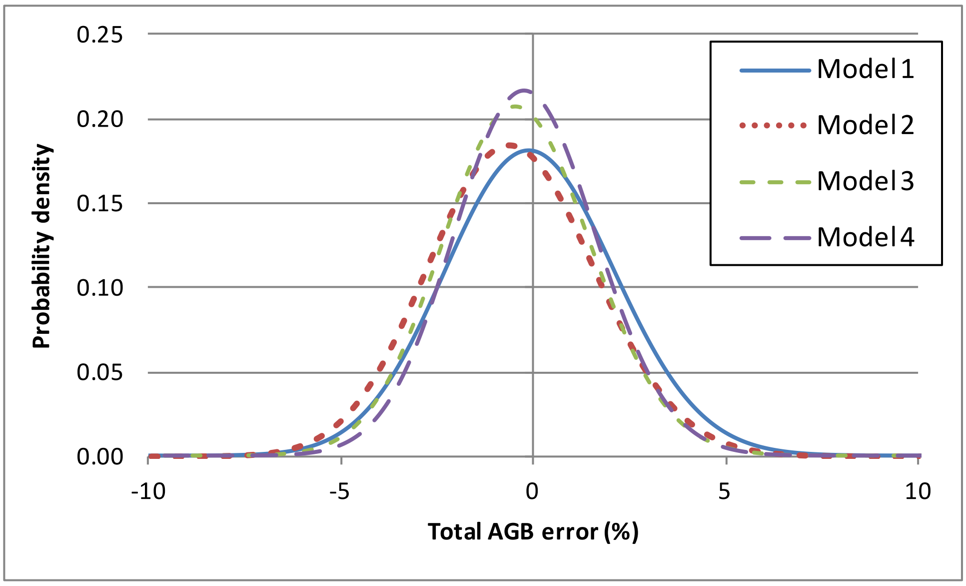
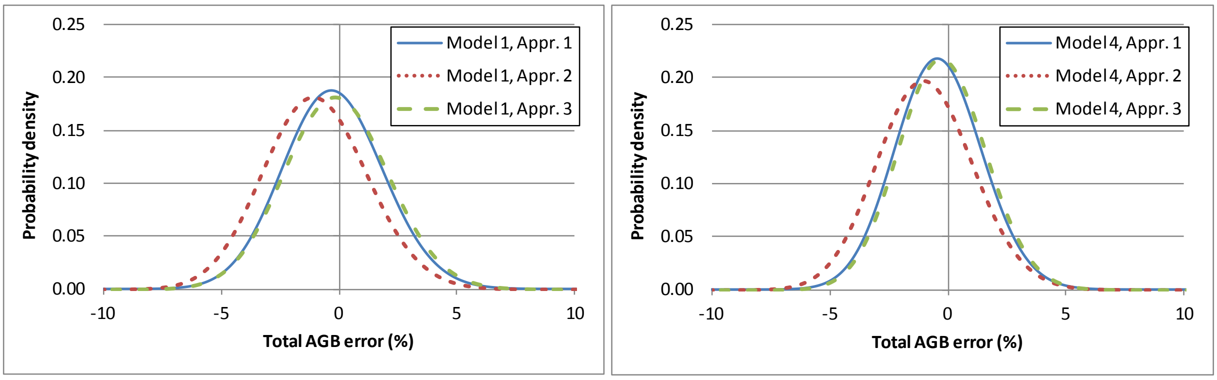


Figure 36: Probability density functions of the total AGB error (%) for equations developed using the third regression approach (*B. chirostachyoides*)

In order to find the best equations for each group of input variables, we did a comparison of the probability density functions of total AGB error across the three regression approaches. The results are shown in Figure 37.



(a) Models that use only variable D (b) Models that use D and H

Figure 37: Comparison of the models across three regression approaches for each group of inputs (*B. chirostachyoides*)

It can be seen from the figure that, with the same model, equations developed using the second regression approach are the least accurate and least robust. Equations derived using the first regression method are the most robust. Equations developed by the third regression approach, although having slightly larger ranges of error, are more accurate than those developed by the first regression approach. Therefore, it is recommended to choose both equations developed by the third approach. Specifically, the following equations are recommended to apply:

$$AGB = 0.5043 \times D^{1.4587} \quad (12)$$

$$AGB = 0.3153 \times D^{1.3450} \times H^{0.2528} \quad (13)$$

With similar arguments with the ones in Section 4.1.5, it can be safe to use the expected values and the ranges of error reported in this section for the Equations 12 and 13 above when predicting the total AGB of 40 (⅓ of 120 trees) or more trees. Their expected values and ranges of error are given in Table 43.

Table 43: Expected values and ranges of total AGB error for Equations 12 and 13 when predicting total AGB of 40 or more trees.

Eq. No.	Equation	Expected value of error (%)	Range of error (95% CL)
12	$AGB = 0.5043 \times D^{1.4587}$	-0.096	-4.34% ÷ 4.28%
13	$AGB = 0.3153 \times D^{1.3450} \times H^{0.2528}$	-0.229	-3.78% ÷ 3.43%

It can be seen from the table that the inclusion of H only slightly improves the robustness (but degrades the accuracy) of the prediction. Heights of standing bamboos, however, are quite difficult to measure accurately. Therefore, it is recommended that for *B. chirostachyoides* forests, it is not necessary to use the parameter H in biomass prediction.

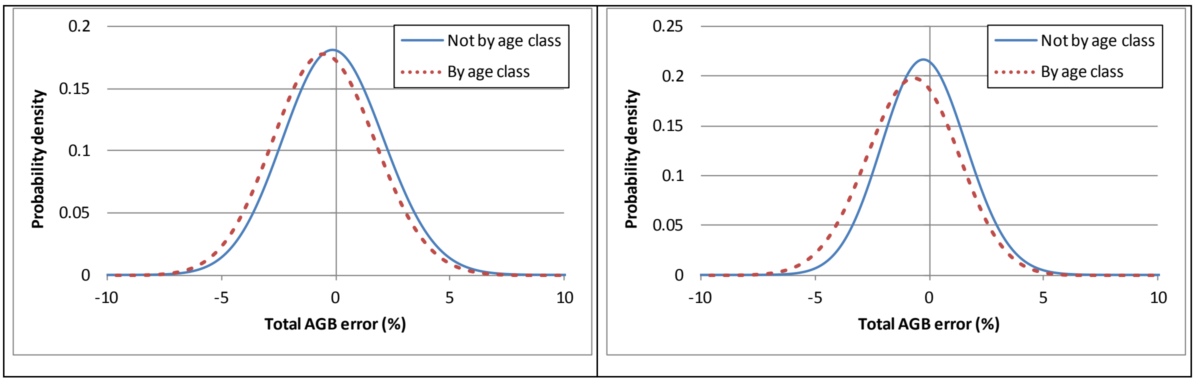
5.3.2 Development of allometric equations for each age class

In order to see whether the development of allometric equations specified for each age group of the bamboos can improve the biomass prediction, we performed an experiment to generate the probability density functions for Models 1 and 4 using the third regression approach (since they are proved to be the best for *B. chirostachyoides*) for each bamboo age class. The results are provided in Table 44. The comparison of two approaches: (i) using one equation for all age classes and (ii) using three equations specified for each age class is shown graphically in Figure 38.

Table 44: Properties of the probability density functions of the total AGB error (%) for the equations developed for each age class using the third regression approach

Model	α	σ	μ	Mean	Median	Mode	f_{max}	R^2	95% Confidence Interval		
									Lower	Upper	Range
1	0.0070	0.0159	-0.0035	-0.484	-0.502	-0.538	0.1776	1.0000	-4.84	3.97	8.81
4	-0.0113	-0.0225	0.0081	-0.746	-0.723	-0.678	0.1982	0.9999	-4.76	3.14	7.90

It can be seen that when developing equations specified to each age class of bamboos, both the robustness and the accuracy of the prediction are degraded. Therefore, it is recommended not to develop age class-specific AEs for *B. chirostachyoides.*



Model 1	Model 4

Figure 38: Comparison of two approaches: (i) using one equation for all age classes and (ii) using three equations specified for each age class (the third regression approach)

4.3.7. Development of allometric equations for each bamboo component

Regression analyses using Model 1 and the third approach were undertaken to develop the AEs for calculating the stem, branch and leaf dry biomass of the bamboos. Cross validation tests are also conducted to estimate the means and ranges of error for these equations. The results are given in Table 45 and Figures 42 – 44 below. The results show that the allometric equations for estimating branch and leaf biomass from DBH have very large ranges of error and should be used with care in practice. An attempt to develop age-class-specific AEs for branch and leaf has been made but no clear improvement on the accuracy as well as robustness of prediction was observed (data not shown).

Table 45: Results of regression analyses using Model 1 and the third regression approach for each part of bamboos

Part	Parameter *a*				Parameter *b*				Error mean (%)	Range of error (%)
	Estimate	Std. err.	t value	Pr > |t|	Estimate	Std. err.	t value	Pr > |t|		
Stem	0.482	0.048	10.063	<0.001	1.459	0.073	20.086	<0.001	-0.275	-4.46 ÷ 4.05
Branch	0.029	0.009	3.115	<0.005	1.212	0.195	6.231	<0.001	0.508	-20.80 ÷ 26.53
Leaf	0.039	0.016	2.405	<0.05	0.909	0.255	3.564	<0.001	0.060	-20.30 ÷ 24.46

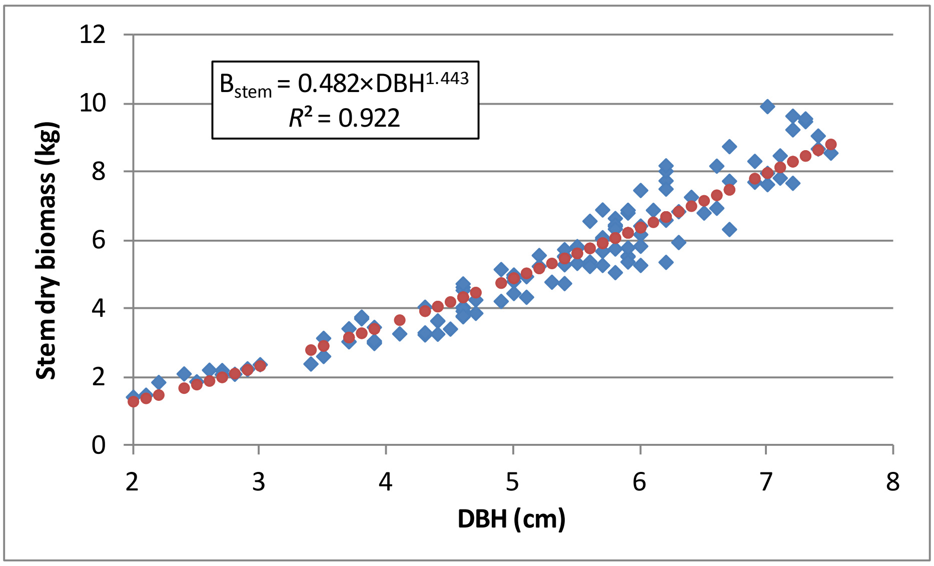


Figure 39: Allometric equation relating the stem dry biomass (kg) with DBH (cm) for all age classes.

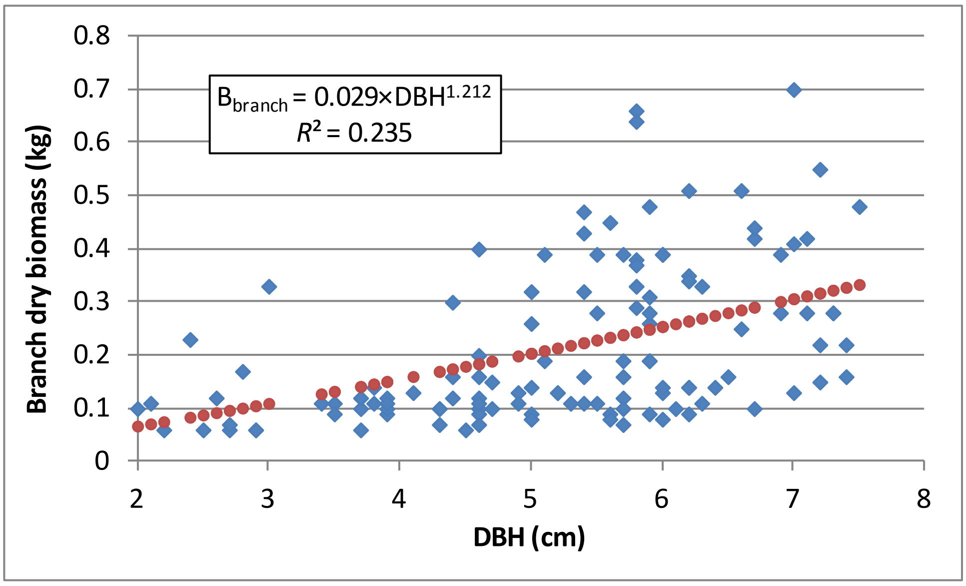


Figure 40: Allometric equation relating the branch dry biomass (kg) with DBH (cm) for all age classes

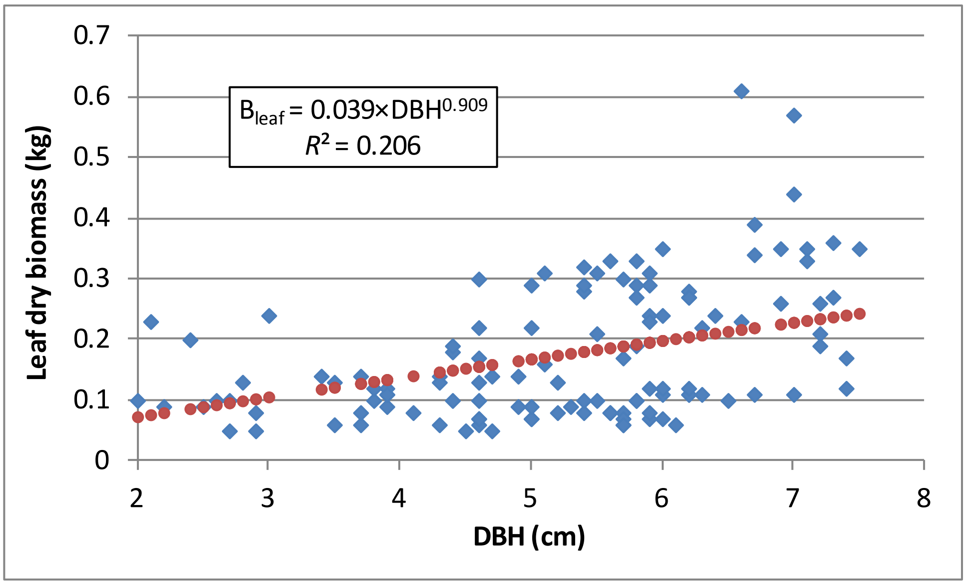


Figure 41: Allometric equation relating the leaf dry biomass (kg) with DBH (cm) for all age classes

CONCLUSIONS AND RECOMMENDATIONS

This report describes the process of developing biomass allometric equations and biomass conversion and expansion factors for biomass estimation of the evergreen broadleaved and bamboo forests in the North East Region of Vietnam. Destructive sampling was done to collect biomass data of sample trees and use these data as dependent variables in the multiple regression analysis. Equations from various different statistical models and regression approaches were developed and compared. For equations that developed using the least squares approach, the adjusted R^2 was used for comparison. For equations developed using the maximum likelihood approach, the AICc was used as for comparison. Cross validation tests were conducted to assess the errors of prediction and compare the equations across different regression approaches. For woody forests, the best chosen AEs were compared with previously published AEs, including those of Basuki *et al.* (2009), Brown (1997) and Chave *et al.* (2005).

For evergreen broadleaf forest, analyzed results of 9 statistical models using three regression approaches have lead to the recommendation of using the following four equations, which are the best for each group of input variables:

Equation[1]	**Expected value of error**[2] **(%)**	**Range of error**[3] **(95% CL)**
$AGB = 0.1142 \times D^{2.4451}$	1.2603	-11.85 ÷ 15.55
$AGB = 0.0547 \times D^{2.1148} \times H^{0.6131}$	-0.5614	-13.08 ÷ 13.21
$AGB = 0.2176 \times D^{2.3825} \times \rho^{0.7996}$	1.0463	-8.17 ÷ 11.46
$AGB = 0.1173 \times (D^2 H^{0.7} \rho)^{0.9898}$	-0.3002	-8.14 ÷ 8.24

[1] AGB is the above-ground biomass in kg; D is the diameter at breast height in cm; H is the height in m; and ρ is the wood density in g/cm^3 of the tree.

[2] The error here means the error (in percentage) of the predicted total AGB as compared to the measured total AGB of a set of trees.

[3] These ranges of error apply when predicting the total AGB for datasets of 72 or more trees. For datasets with smaller number of trees, the ranges of error may be larger.

The results also indicated that the inclusion of height and wood density as additional input variables contributes to the improvement of prediction. Therefore, whenever these variables are available, the equations that use them should be applied. Moreover, the inclusion of wood density improves the robustness of prediction much more than the inclusion of height so wood density should be given the first priority when considering additional variables. The comparison with previously published AEs has shown that all three previously published AEs tend to over-estimate the total AGB of the trees in the studied dataset. The total AGB errors of the Basuki *et al.* (2009), Brown (1997) and Chave *et al*. (2005) AEs for the current dataset are 3.49%, 44.75% and 25.55%, respectively. These results imply that countries need to develop their own specific AEs in order to improve the certainty of biomass prediction and carbon stock assessment.

An attempt was also made to estimate BCEF and BEF for evergreen broadleaf forests. The results show that BCEF and BEF do not depend on DBH but vary around a constant, which is 0.642 for BCEF and 1.238 for BEF.

For *Indosasa angustata* bamboo forest, analyzed results of four statistical models using three regression approaches have lead to the recommendation of using the following AE:

Equation	Expected value of error (%)	Range of error[1] (95% CL)
$AGB = 0.2184 \times D^{1.8517}$	-0.031	-12.59 ÷ 14.28

[1]These ranges of error apply when predicting the total AGB for datasets of 23 or more trees. For datasets with smaller number of trees, the ranges of error may be larger.

The analyzed results also show that the inclusion of variable H does not improve the accuracy nor the robustness of the prediction. Equations developed specifically for each age class improve the robustness but degrade the accuracy of the prediction. Therefore, for *Indosasa angustata* forest, it is recommended not to include H and age class as input variables for biomass prediction.

For *B. chirostachyoides* bamboo forests, analyzed results recommend the use of the following two equations:

Equation	Expected value of error (%)	Range of error[1] (95% CL)
$AGB = 0.5043 \times D^{1.4587}$	-0.096	-4.34% ÷ 4.28%
$AGB = 0.3153 \times D^{1.3450} \times H^{0.2528}$	-0.229	-3.78% ÷ 3.43%

[1]These ranges of error apply when predicting the total AGB for datasets of 40 or more trees. For datasets with smaller number of trees, the ranges of error may be larger.

The results show that the inclusion of H only slightly improves the robustness (but with the price of slightly reducing the accuracy) of the prediction. Because heights of standing bamboos are quite difficult to measure accurately, it is recommended that for bamboo forests, it is not necessary to include the variable H in biomass prediction.

Age-class specific AEs were also developed for *B. chirostachyoides* forest. The analyzed results show that age class specific AEs does not improve the robustness nor the accuracy of biomass prediction. Thus, it is suggested not to include the age class variable in biomass prediction for *B. chirostachyoides* forest.

In order to improve the certainty of biomass prediction in the studied region, the next studies should concentrate on the development of AEs and BCEFs specified to each tree family or wood density class. Since the range of error of the best model for *Indosasa angustata* forests is still quite large (> ±10%), destructive sampling of more sample trees for *Indosasa angustata* forests is also recommended.

REFERENCES

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

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

Brown, S., 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO. Forestry Paper 134, Rome.

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

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. Oecologia 145, 87-99.

Chave, J., Condit, R., Aguilar, S., 2004. Error propagation and scaling for tropical forest biomass estimates. Phil. Trans. R. Soc. Lond. B 359, 409–420.

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

FAO, 1998. FRA 2000 Terms and Definition. FRA Working Paper 1. FAO Forestry Department.

Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2, 13.

Henry, M., 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, 1375-1388.

ICRAF, 2011. Guidelines for establishing regional allometric equations for biomass estimation through destructive sampling.

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

IPCC, 2003. Annex A Glossary. In: Good Practice Guidance for Land Use, Land Use Change and Forestry. Institute for Global Environmental Strategies (IGES). Japan.

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, 199-209.

UN-REDD Vietnam & FAO, 2012. Guidelines on Destructive Measurement for Forest Biomass Estimation. Draft version. UN-REDD Vietnam, Hanoi.

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

Yamakura, T., Hagihara, A., Sukardjo, S., Ogawa, H., 1986. Aboveground biomass of tropical rainforest stands in Indonesian Borneo. Plant Ecology 68 (2), 71–82.

APPENDICES

Appendix 1. Glossary of basic terms

A glossary of the following key terms is adapted from Good Practice Guidance for Land Use, Land Use Change and Forestry[2].

1. Biomass

Organic material both above ground and below ground, and both living and dead, e.g., trees, crops, grasses, tree litter, roots etc. Biomass includes the pool definition for above and below ground biomass.

2. Biomass of forests

Biomass is defined as the total amount of aboveground living organic matter in trees expressed as oven-dry tons per unit area (tree, hectare, region, or country). Forest biomass is classified into above ground biomass and below ground biomass.

Above ground biomass is living biomass above the soil including stem, stump, branches, bark, seeds, and foliage.

Below ground biomass is all living biomass of live roots. Fine roots of less than (suggested) 2 mm diameter are sometimes excluded because these often cannot be distinguished empirically from soil organic matter or litter.

3. Basic wood density

Ratio between oven dry mass and fresh stem wood volume without bark. It allows the calculation of woody biomass in dry matter mass. Basic wood density is normally expressed in g/cm3 or ton/m3.

4. Biomass Conversion and Expansion Factor (BCEF)

Ratio between above-ground biomass in tonnes and growing stock in m^3.

5. Biomass Expansion Factor (BEF)

Ratio between above-ground biomass and biomass of growing stock. This factor is often used to expand biomass of growing stock, or commercial round wood volume, or growing stock volume increment data, to account for non-merchantable biomass components such as branches, foliages, and non-commercial trees.

6. Carbon fraction

Carbon fraction is a carbon content expressed in per cent (%) in dry oven mass of certain component of forests (stem, branches, foliage, root, etc).

7. Carbon pools

Carbon pool is reservoir containing carbon. There 5 carbon pools in a forests considered for forest carbon estimation that are: carbon in live trees (above and below ground), carbon in dead trees and wood, carbon stock in under-storey vegetation (seedlings, shrubs, herbs, grasses), carbon stock in forest floor (woody debris, litter, humus) and soil organic carbon.

---

[2] IPCC, 2003. Annex A Glossary. In: Good Practice Guidance for Land Use, Land Use Change and Forestry. Institute for Global Environmental Strategies (IGES). Japan.

8. Carbon stock

Carbon stock is the quantity of carbon in a pool.

9. Forest

Forest is a minimum area of land of 0.05 – 1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10 – 30 per cent with trees with the potential to reach a minimum height of 2 – 5 meters at maturity in situ (in place). A forest may consist either of closed forest formations where trees of various stories and undergrowth cover a high portion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10 – 30 per cent or tree height of 2 – 5 meters are included under forest, as are areas normally forming part of the forest area which are temporarily un-stocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest.

FAO provides the definition of a forest which is land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use[3].

10. Root to shoot ratio (RS)

RS is defined as a ratio of below ground biomass to above ground biomass of trees. RS is normally used to estimate below ground biomass of trees if above ground biomass of trees is known.

[3] FAO, 1998. FRA 2000 Terms and Definition. FRA Working Paper 1. FAO Forestry Department.