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Tree allometric equation development for estimation of forest above-ground biomass in Viet Nam

Part A - Introduction and Background of the Study

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Tree allometric equation development for estimation of forest above-ground biomass in Viet Nam Part A - Introduction and Background of the Study

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Executive summary

Viet Nam is one of the few tropical countries, whose forests have shifted along the forest transition curve, to exhibit net forest increase. National efforts towards the establishment of a system for monitoring forests to assess emission reductions and removals include the implementation of specific allometric models for Viet Nam. Under the UN-REDD program in Viet Nam, six institutions have been working on the development of a database containing information such as existing allometric equations and wood densities, the identification of necessary and priority, the development of guidelines for the establishment of allometric models, collection of field data and the development of new allometric equations.

The results of the work are consolidated in a series of reports composed of parts A and B. Part A is this report which provides the introduction and background, and summaries the main outcomes of all six studies undertaken for the development of allometric equations as mentioned above. Part B is composed of six further reports for the six respective studies as outlined in the following.

In total, 861 trees were measured in evergreen broadleaf forest from 16 plots, 123 trees in deciduous forests (2 plots) and 378 bamboo trees (6 plots). Measurements included tree diameter, height, wood density, volume, biomass, and crown area. Wood density and dry mass measurements were carried out in three laboratories. Allometric equations were developed for total aboveground tree biomass (AGB), the AGB of each tree compartment (stem, branches, and leaves), tree volume and height – diameter correlation. Biomass expansion factors (defined as the ratio between stem AG and total AGB) were also calculated.

Models developed in **evergreen broadleaf forests in the South Central Coastal region**, by Department of Forest Resource and Environment Management of Tay Nguyen University (Part B-1), showed a lower average deviation (S% = 13%-16%) than generic models (Brown, 1997 offered a model with S% = 43% -107%, Chave et al., 2005 with S% = 52% -94%, and Basuki et al., 2009 with S% = 26% - 30%). It is recognized that apart from the variables of DBH and H, WD is important to increase accuracy of AGB estimation as it reflects biomass by species. [Part B-1]

In **evergreen broadleaf and bamboo forests in the North East region**, the North-West Sub-Forest Inventory and Planning Institute (FIPI) measured 215 trees and 70 bamboos in four one-ha plots and developed tree allometric equations and biomass conversion and expansion factors using the following input variables: diameter at breast height (DBH), tree height (H), and wood density (WD). The results indicated that inclusion of H and WD as additional input variables contribute significantly to improvement of prediction. The comparison with previously published equations showed that equations from Basuki *et al.* (2009), Brown (1997) and Chave *et al*. (2005) tended to over-estimate total tree biomass by about 3.49%, 44.75% and 25.55%, respectively. Attempt to develop BEF for evergreen broadleaf forests revealed that BEFs do not depend on DBH but vary around a constant of about 1.238. Regarding allometric equations for *Indosasa angustata* and *B. chirostachyoides* bamboo forests, the analysis showed that the inclusion of H does not improve accuracy or robustness of the prediction. On the other hand, inclusion of age class improved the robustness but degrade accuracy. Therefore, for bamboo forests, it is recommended not to include H and age class as input variables for biomass prediction. [Part B-2]

In **evergreen broadleaf forest in the North Central Coastal region**, FIPI measured 110 trees in two one-ha plots and developed tree allometric equations and biomass conversion and expansion factors using the following input variables: DBH, H, and WD. The results of regression analyses indicate that the inclusion of H and WD as additional input variables contributes to the improvement of the model. Moreover, the inclusion of WD improved the model more than the inclusion of H. Cross validation tests were undertaken to assess the

performance of the developed equations in practice and draw the ranges of errors for them. When comparing with other equations, results showed that the Brown's (1997) equation tended to over-estimate biomass. On the other hand, Basuki *et al.* equation slightly under-estimated the biomass of the large sample trees. [Part B-3]

In **evergreen broadleaf and bamboo** (Dendrocalamus barbatus) **forests in the North Central Coastal region**, the Viet Nam Forestry University measured 221 trees and 100 Bamboos in five one-ha plots and developed tree allometric equations and biomass conversion and expansion factors using the following input variables: DBH, H, and WD. The deviation of the models developed for evergreen broadleaved forest ranged from 5.74 to 28.72, which was better than the generic models (S% = 67.60 for Brown model and 47.09 for Chave et al. model). The average BEF was 1.24 ± 0.16. Models were also developed bamboo tree compartments. The model for total ABG presented a 7.41% deviation. [Part B-4]

In **evergreen broadleaf, deciduous, and bamboo forests in the South East region**, the Center for Forest Information and Consultancy of FIPI (CFIC) measured 178 trees and 138 Bamboos in three one-ha plots and developed tree allometric equations and biomass conversion and expansion factors using the following input variables: DBH, H, and WD. Results indicated that inclusion of H and WD as additional input variables contributes to the improvement of the prediction. Comparison with previously published equations from Basuki et al. (2009) and Brown (1997) tended to overestimate tree AGB by 11.2%, 57.2% and 6.7% and 39.7% in evergreen and deciduous forests respectively. On the other hand, equations form Chave et al. (2005) fitted well in deciduous forests but over-estimated biomass in evergreen forests by 35.8%. Attempts to develop BCEF and BEF revealed that those variables vary around a constant of 0.715-0.834 and 1.256-1.396 in evergreen and deciduous forests respectively. When comparing results from evergreen and deciduous forests, it appeared that WD in biomass prediction of deciduous forests was less significant. For bamboo forests, results showed that inclusion of H slightly improved accuracy as well as the robustness of the prediction. Because bamboo height is difficult to measure, it is recommended to consider bamboo diameter and age-class. [Part B-5]

In **evergreen broadleaf, deciduous, and bamboo** (Bambusa procera) **forests in the Central Highland region**, the Forest Science Institute of Viet Nam measured 11+685 trees and 138 bamboos three one-ha plots. Results showed that there was strong relationship between AGB and DBH, H and WD. Results indicated that compared to models from Brown (1997), Chave (2005) and Basuki et al (2009), suggested models developed in this study can generate higher reliability biomass estimation in Central Highland forests of Viet Nam. [Part B-6]

The results obtained from the six institutions reveal that specific biomass estimates for each forest type in the ecological regions of Viet Nam improve reliability and accuracy of biomass and carbon stock assessment for all forest types. All the eco-region and forest-type specific allometric equations have a deviation at least half of the deviation of generic models. These results lead us to the recommendation that when possible, destructive measurements are necessary to test validity of existing allometric equations or to develop country-and-forest-specific equations. Identification of adequate allometric equations and methods is a significant step toward improvement of national biomass assessment and accurate carbon stock change factors.

Table of the equations developed

Eco-region	Forest type	Equation[1]	R^2	Average deviation (S%)	Expected value of error[2] (%)	Range of error[3] (95% CL)	Institution
South East	Evergreen Broadleaf	$AGB = 0.1277 \times D^{2.3943}$	NC	20.94	0.909	-12.78 ÷ 16.76	CFIC
South East	Evergreen Broadleaf	$AGB = 0.0530 \times (D^2H^{0.7})^{1.0072}$	NC	19.40	-0.467	-13.54 ÷ 14.36	CFIC
South East	Evergreen Broadleaf	$AGB = 0.2328 \times (D^{2.4}\rho)^{0.9933}$	NC	17.02	0.679	-10.05 ÷ 12.38	CFIC
South East	Evergreen Broadleaf	$AGB = 0.0968 \times (D^2H^{0.7}\rho)^{10037}$	NC	15.46	-0.666	-10.81 ÷ 10.28	CFIC
South East	Deciduous forest	$AGB = 0.0670 \times D^{2.5915}$	NC	16.65	-1.082	-12.92 ÷ 13.33	CFIC
South East	Deciduous forest	$AGB = 0.0154 \times (D^2H^{0.7})^{1.1682}$	NC	16.11	-0.913	-11.68 ÷ 11.82	CFIC
South East	Deciduous forest	$AGB = 0.0560 \times (D^{2.4}\rho)^{1.1655}$	NC	19.90	-0.681	-11.46 ÷ 11.84	CFIC
South East	Deciduous forest	$AGB = 0.0159 \times (D^2H^{0.7}\rho)^{1.2275}$	NC	23.18	-1.850	-10.79 ÷ 7.34	CFIC
South East	bamboo forest *(Bambusa balcoa)*	$AGB = 0.1006 \times D^{2.2220}$	NC	NC	0.327	-6.76 ÷ 7.84	CFIC
South East	bamboo forest *(Bambusa balcoa)*	$AGB = 0.0644 \times D^{1.9696}H^{0.3426}$	NC	NC	0.265	-6.66 ÷ 7.61	CFIC
Central Highland	Evergreen Broadleaf	$AGB = 0.222 * DBH^{2.387}$	0.96	17.67	NC	NC	RCFEE
Central Highland	Broadleaf evergreen	$AGB = 0.098 * \exp(2.08 * \ln(DBH) + 0.71 * \ln(H) + 1.12 * \ln(WD))$	0.98	14.17	NC	NC	RCFEE
Central Highland	Deciduous forest	$AGB = 0.14 * DBH^{2.31}$	0.93	26.97	NC	NC	RCFEE
Central Highland	Bamboo forest (*Bambusa procera)*	$AGB = 0.182 * DBH^{2.16}$	0.86	23.78	NC	NC	RCFEE
South Central Coastal	Evergreen Broadleaf	$AGB = \exp(-2.24267 + 2.47464 * \ln(DBH))$	0.98	15.1-23.0	NC	NC	TNU
South Central Coastal	Evergreen Broadleaf	$AGB = -2.23222 + 0.744261 * \log(DBH^2 * H) + 1.13674 * \log(WD) + 0.17046 * \log(DBH^2 * CA)$	0.99	13.4-17.2	NC	NC	TNU
North Central Coastal	Evergreen Broadleaf	$\ln(AGB) = -1.0703 + 2.3028 * \ln(D) + 1.2901 * \ln(WD)$	*0.97*	5.74	NC	NC	VFU
North Central Coastal	Bamboo forest (*Dendrocalamus barbatus*)	$AGB = 0.1726 * D^{2.0545}$	0.92	7.41	NC	NC	VFU
North Central Coastal	Evergreen Broadleaf	$AGB = 0.1245 \times D^{2.4163}$	NC	25.66	0.101	-16.96 ÷ 20.61	FIPI
North Central Coastal	Evergreen Broadleaf	$AGB = 0.0421 \times (D^2H)^{0.9440}$	NC	24.67	-1.205	-16.67 ÷ 17.70	FIPI
North Central Coastal	Evergreen Broadleaf	$AGB = 0.2105 \times (D^{2.4}\rho)^{1.0025}$	NC	16.23	0.600	-14.03 ÷ 17.67	FIPI
North	Evergreen	$AGB = 0.0704 \times (D^2H\rho)^{0.9389}$	NC	13.73	-0.737	-12.32 ÷ 11.70	FIPI

Central Coastal	Broadleaf						
North East	Evergreen Broadleaf	$AGB = 0.1142 \times D^{2.4451}$	NC	27.34	1.2603	-11.85 ÷ 15.55	Sub-FIPI
North East	Evergreen Broadleaf	$AGB = 0.0547 \times D^{2.1148} \times H^{0.6131}$	NC	25.76	-0.5614	-13.08 ÷ 13.21	Sub-FIPI
North East	Evergreen Broadleaf	$AGB = 0.2176 \times D^{2.3825} \times \rho^{0.7996}$	NC	15.38	1.0463	-8.17 ÷ 11.46	Sub-FIPI
North East	Evergreen Broadleaf	$AGB = 0.1173 \times (D^2 H^{0.7} \rho)^{0.9898}$	NC	13.02	-0.3002	-8.14 ÷ 8.24	Sub-FIPI
North East	Bamboo forest (*Indosasa angustata)*	$AGB = 0.2184 \times D^{1.8517}$	NC	NC	-0.031	-12.59 ÷ 14.28	Sub-FIPI
North East	Bamboo forests (*B. chirostachyoides*)	$AGB = 0.5043 \times D^{1.4587}$	NC	NC	-0.096	-4.34 ÷ 4.28	Sub-FIPI
North East	Bamboo forests (*B. chirostachyoides*)	$AGB = 0.3153 \times D^{1.3450} \times H^{0.2528}$	NC	NC	-0.229	-3.78 ÷ 3.43	Sub-FIPI

[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/cm3 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.

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List of acronyms

AGB	Above Ground Biomass
CFIC	Center for Forest Inventory and Consultancy
CH	Central Highlands region
CDM	Clean Development Mechanism
CF	Correction Factor
CA	Crown Area
CD	Crown Diameter
Dec	Deciduous forests
DBH	Diameter at Breast Height
EB	Evergreen Broadleaf forests
FAO	Food and Agriculture Organization of the United Nations
FIPI	Forest Inventory and Planning Institute
GoV	Government of Viet Nam
H	Height
IPCC	Inter-governmental Panel on Climate Change
JICA	Japan International Cooperation Agency
MARD	Ministry of Agriculture and Rural Development
NCC	North Central Coastal region
NE	North East region
NW	North West region
Sub FIPI	North-west Sub-office of Forest Inventory and Planning Institute
RRD	Red River Delta region
RCFEE	Research Centre for Forest Ecology and Environment
SCC	South Central Coastal region
SE	South East region
SW	South West region
TNU	Tay Nguyen University
UN-REDD	UN-REDD Programme
VAFS	Viet Nam Academy of Forest Sciences
VFU	Viet Nam Forestry University
VRO	Viet Nam REDD+ Office
WD	Wood Density

1 INTRODUCTION

Viet Nam is one of the few tropical countries, whose forests have shifted along the forest transition curve to exhibit net forest increase. Forest area has increased from 9.18 to 13.38 million hectares between 1990 and 2010 (MARD 2009; MARD 2012). Gains in forest area are mainly attributed to the establishment of forest plantations. Despite the overall increase, pockets of deforestation are also present and forest degradation continues to be a problem in natural forests. It is against this backdrop that the Government of Viet Nam (GoV) has been investing considerable effort in REDD+ readiness, including with the support of a number of international development partners.

The UN-REDD Programme is an initiative to support efforts contributing to the implementation of REDD+ in Viet Nam. The accounting system of emissions reductions in the forestry sector must be as much as possible transparent, accurate, consistent, comparable and complete. The basic formula for the IPCC greenhouse gas balance calculation is based on activity data (extent to which a human activity takes place) and emission factors (coefficients which quantify the emissions or removals per unit of activity). Two methods are proposed for the calculation of emission factors: stock difference and gain - loss methods. In both cases, allometric equations are needed to perform the calculation or verification of forest carbon stock change factor. Inappropriate use of allometric equations, tables and volume expansion factors can lead to significant errors. The greater the uncertainty, the less credible is the reduction of emissions. One of the activities implemented by the UN-REDD Programme for Viet Nam is supporting the development of allometric equations.

The activities were implemented as a series of work undertaken through the UN-REDD Programme for Viet Nam with technical assistance from FAO, towards the improvement of country-specific emission factors for Viet Nam. The series of activities include;

1. The development of the **Destructive measurement guideline for the estimation of forest biomass in Viet Nam** (UN-REDD Viet Nam, 2012);
2. Training of technical staff on allometric equation modeling[1];
3. Sampling and destructive measurement for forest types in eco-regions;
4. Analysis, model development and documentation;
5. Development of a database for all existing country-specific allometric equations.

This report is directly an output of item 4 above, which is based on the activities of item 3. The results of the work are consolidated in a series of reports composed of parts A and B. Part A is this report which provides the introduction and background, and summaries the main outcomes of all six studies undertaken for the development of allometric equations as mentioned above. Part B is composed of six further reports for the six respective studies by different national institutions, namely, the Forest Science Institute of Viet Nam, Forest Inventory Planning Institute, North-West Sub-FIPI, Center for Forest Information and Consultancy, Viet Nam Forestry University and Tay Nguyen University.

1.1 Institutional arrangements

These series of activities were conducted by five national institutes and organization, namely, Forest Inventory and Planning Institute (FIPI), North-west Sub-FIPI, Center for Forest Inventory and Consultancy (CFIC), Viet Nam Forestry University (VFU), Tay Nguyen University (TNU), and the Research Center for Forest Ecology and

[1] National technical staff training on allometric equations (AE) under the UN-REDD Programme on 18-22 June 2012. Materials and information can be accessed at: http://Viet Nam-redd.org/Web/Default.aspx?tab=eventdetail&zoneid=107&subzone=158&itemid=467&lang=en-US

Environment (RCFEE, under VAFS) as coordinator. The study was financed by UN-REDD programme and technically supervised by FAO and the Viet Nam REDD+ Office (VRO). Most tasks itemized above were carried out with the involvement of all institutes named above.

1.2 Forest stratification of the country

To support the development of a forest monitoring system and the evaluation of forest resource, a stratification of the land based on eco-regions and forest-types was adopted. This stratification has been used for the identification of areas where trees should be measured (item 3) for the development of allometric equations (item 4). The eco-regions were adopted from the results of the study on Forest Ecological Stratification in Viet Nam (UN-REDD Viet Nam, 2011). The recommended eight eco-regions are applied, however, for practical considerations, in this study each province was designated to a single eco-region, avoiding a single province straddling more than one eco-region. The resulting eco-regions are in Table 1-1.

Table 1-1: Eco-regions (UN-REDD Viet Nam, 2011)

Eco-regions	Provinces	Forest cover (2011) Million ha	% of national forest cover (2011)
North-west (NW)	Dien Bien, Lai Chau, Son La, Hoa Binh	1.61	12
North-east (NE)	Lao cai, Yen Bai, Ha Giang, Tuyen Quang, Phu Tho, Vinh Phuc, Cao Bang, Lang Son, Bac Kan, Thai Nguyen, Quang Ninh, Bac Giang	3.50	26
Red River Delta (RRD)	Hai Phong, Hai Duong, Bac Ninh, Hung Yen, Ha Noi, Thai Binh, Nam Dinh, Ha Nam, Ninh Binh	0.96	1
North Central Coastal (NCC)	Thanh Hoa, Nghe An, Ha Tinh, Quang Binh, Quang Tri, Thua Thien Hue	2.83	21
South Central Coastal (SCC)	Da Nang, Quang Nam, Quang Ngai, Binh Dinh, Phu Yen, Khanh Hoa, Ninh Thuan, Binh Thuan	2.07	15
Central Highlands (CH)	Kon Tum, Gia Lai, Dak Lak, Dak Nong, Lam Dong	2.85	21
South-east (SE)	Ba Ria-Vung Tau, Dong Nai, Binh Duong, Binh Phuoc, Tay Ninh, Ho Chi Minh	0.42	3
South-west (SW)	Long An, Ben Tre, Dong Thap, Soc Trang, Vinh Long, Can Tho, Hau Giang, Tien Giang, Bac Lieu, Ca Mau, Kien Giang, Tra Vinh	0.36	2

(Source: MARD 2012. Decision 2089/QD-BNN-TCLN)

Viet Nam employs a forest type classification categorizing forests according to purpose, geographical condition, tree species composition, timber volume and others (i.e. Circular 34), and the national forest inventory programmes conducted by FIPI have applied a unique coding system of forests for each of the past four inventory cycles. For the purpose of this study, such forest classification was generalized into nine main forest types (adopted from study by JICA 2011) (Table 1-2).

Table 1-2: Forest-type and their distribution

Forest type	Main eco-regions of distribution	% of national forests
1. Evergreen broadleaf forests (including all classes of rich, medium, poor and rehabilitation) (EB)	CH, SCC, NE, NCC, NW	57.3
2. Deciduous forests (Dec)	CH, SE	5.2
3. Bamboo forests	NW, NCC, NE	1.8
4. Mixed wood and bamboo forests	NE, NCC, CH, NW	12
5. Conifer forests	CH, NCC	1.0
6. Mixed conifer and broadleaf forests	CH, NE, SE	0.2
7. Limestone forests		0.4
8. Mangrove forest	NE, SE, SW	0.3
9. Planted forests	Distributed nationally, particularly in NE, NC, SCC	22

(Source: JICA 2011)

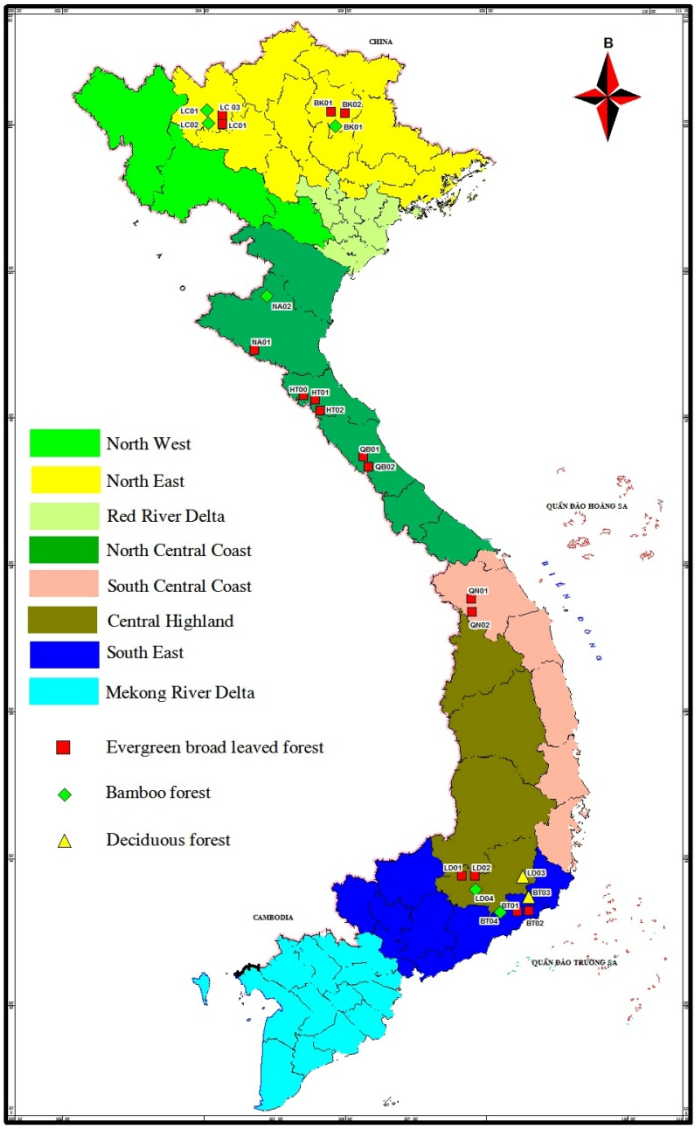
Based on the eco-regions and forest-types stratification, priority was set for the three most dominant forest-types in regions with highest forest cover. The number of plots for sampling (based on the number of trees to be analyzed) was subsequently agreed (Table 1-3). A minimum of 50 trees were felled per plot for woody forest-types (i.e. for EB and Dec), and a minimum of 100 bamboo stems for plot of bamboo forests.

Table 1-3: Number of trees sampled for destructive measurements. Number of sampled tree (number of 1 ha plots)

	NE	NCC	SCC	CH	SE	Total
EB	215 (4)	201 (4) + 110 (2)	110 (2)	115 (2)	110 (2)	861 (16)
Bamboo	69 (3)	51 (1)		138 (1)	120 (1)	378 (6)
Dec				68 (1)	55 (1)	123 (2)

The locations of plots were considered by each institution taking into account representativeness of the plot area, accessibility and cutting permission among other factors (Figure 1-1).

Figure 1-1: Map of survey plot distribution



Survey plots were assigned to institutes as follows;

Institution	Eco-region	Province	Forest-type (# of plots)
RCFEE	CH	Lam Dong	EB (2), Dec (1), Bamboo (1)
FIPI	NCC	Quang Binh	EB (2)
Sub-FIPI	NE	Bac Kan Lao Cai	EB (2), Bamboo (1) EB (2), Bamboo (1)
CFIC	SE	Binh Thuan	EB (2), Dec (1), Bamboo (1)
VFU	NCC	Ha Tinh Nghe An	EB (2), Bamboo (1) EB (2), Bamboo (1)

1.3 Procedures for destructive measurement

Based on the above allocation of forest-type and eco-region, including province, with guidance and endorsement from the VRO, the institutes respectively obtained permits for entry and cutting trees as necessary and prepared for the destructive measurement survey. The details of the destructive measurement survey followed those procedures proposed in the earlier Destructive Measurement Guidelines (UN-REDD Viet Nam, 2012a).[2] All raw data obtained in the surveys were transcribed onto spreadsheet format, and will be archived at VRO together with the report.

1.4 Objectives and scope

The scope of the work covered under the five reports (one for each institute) includes the following for each forest-type and eco-region:

1. Description of forest structure;
2. Tree biomass measurement;
3. Wood density analysis;
4. Development and analysis of allometric equation models to estimate above ground biomass (AGB).

The work covered in the five reports follows the activities related to the development of the tree allometric equations database, identification of the gaps, training on model development and is part of the process to improve the national forest biomass assessment.

2 BACKGROUND

2.1 Biomass assessment and tree allometric equations

The broadest definition of allometry is the linear or non-linear correlation between increases in tree dimensions (Picard et al., 2012). Therefore allometric equations can be used to link difficult to measure variables, such as volume or biomass, to easy-to-measure tree characteristics, diameter or height for example, with statistically determined parameters. The general function form is:

$$y = f(x_i) \qquad \textbf{Equation 2-1}$$

where, y = above ground biomass; xi = forest variables of interest such as diameter at breast height (DBH), height (H), crown area (CA), crown diameter (CD), and wood density (WD).

These equations are of great importance for the estimation of tree volume and biomass, and then to estimate forest carbon stock and carbon stock changes. The quality of theses equations is crucial for ensuring the accuracy of forest carbon estimates and is not only a matter of statistical tools. The errors made all along the process of building these equations should be considered, from the field work to the modeling and the prediction (Picard et al., 2012).

[2] A final version of this Guideline was then developed based on the feedback of its use during the field surveys.

The recommended variables to be measured in order to assess the biomass are tree diameter at breast height, tree height and wood density. The use of diameter and height is easy to understand as they are used in the mathematical formulas for volume calculation. Wood density is also very important as it differs a lot among tree genus and species (Chave et al., 2006). It is defined as the ratio of dry biomass with fresh volume without bark (IPCC, 2006).

Statistical indicators can also be used for comparison and assessment of the goodness of fit. The models should be compared with generic models in terms of error but the robustness of a model is also dependant of the number of trees sampled for the modeling. Picard et al. (2012) developed guidelines to support the development of tree allometric equations.

2.2 Literature review of allometric equations for tropics

Several generic models have been developed for the tropical forests and can be compared to the newly developed and country specific equations. Henry et al., (2010) applied the variable WD while in developing allometric equations for African tropical forests. The authors indicated that WD is influenced by several factors including terrain and soil nutrients. Additionally, they also found using CD for estimate of biomass was better when compared to use of tree height in the case of a African tropical rainforest. The equation generated by Henry et al., (2010) is:

$$\mathrm{y} = 0.03 \times \mathrm{DBH}^{0.0816} \times \mathrm{CD}^{0.03} + \mathrm{WD}^{0.04} \qquad \textbf{Equation 2-2}$$

Allometric model selection with different alternative variables gave different reliability according to Chave et al., (2004). A research conducted in Panama showed that apart from DBH and H, the variable of WD was necessary. Similarly, Basuki et al., (2009) pointed out the presence of WD in the model resulted in high reliability for their research in lowland dipterocarp forests. Variables of CD or CA improved reliability and accuracy of the biomass estimates by Dietz et al., (2011), Henry et al., (2010), Johannes et al., (2011).

Numerous publications have suggested power models are suitable for building allometric equations based on one or more variables. The model form is:

$$y = a \times x_i^b \Leftrightarrow y = \exp(A + b \times ln(x_i)) \Leftrightarrow \ln(y) = A + b \times \ln(x_i) \qquad \textbf{Equation 2-3}$$

$where\ A = \ln(a)$

Pearson (2007) suggested using this function for tree species and forest types in the United States. Some authors used the second order exponential function of parabolic as Brown (1989, 1997). Basuki et al., (2009) used the model of dipterocarp forest biomass to compare the higher-order parabolic functions of Brown (1989), Chave (2005) using average deviation. The result indicated the transformed exponential function as below gave smaller deviation and higher reliability.

$$\ln(AGB) = a + b \times \ln(DBH) \qquad \textbf{Equation 2-4}$$

For allometric equations using WD, IPCC (2006) refers to Baker et al., (2004b); Barbosa and Fearnside (2004); CTFT (1989); Fearnside (1997). Reyes et al., (1992) provided a list of WD of tropical tree species. WD found in international datasets could complement the existing national WD database to improve tree biomass calculation.

In some developed countries, allometric functions are available for most of their forest tree species: in the United States Jenkins et al., (2004) had compiled more than 1,700 allometric equations for more than 100 species of trees from 177 sample trees, mainly estimating biomass based on DBH as predictor.

Brown (1989 – 2001) summarized models of allometric equations developed for tropical areas around the world including dry forest, moist forest, swamp forest and coniferous forest. Data sources were from a variety of trees destructively sampled from three tropical zones with a total of 371 sample trees with diameter ranging 5-148 cm. Of these models, the model developed for moist forests can be applied to low mountainous evergreen broad-leaved forests of Viet Nam, considering the similarity of site conditions (i.e. average rainfall 1,500-4.000 mm, with one dry season during the year).

The models mentioned above were made based on limited data not collected in Viet Nam, nor assessed for relevance and reliability in the rainforest conditions of Viet Nam. Also, it is noteworthy that Ketterings et al., (2001) has suggested that the biomass models of Brown (1989) based on 168 sample trees may not be representative of the diversity of tree species as well as different types of tropical forests.

Chave et al., (2005) synthesized results of 27 published and unpublished data sources of sample trees which were destructively sampled to measure forest ABG from the three continents of America, Asia, and Oceania. The total number of sample trees was 2,410 with DBH of 5 cm and over. From these sample trees allometric equations were developed and selected. The most suitable models for the tropical forest areas are as follows:

Forest type	Author	Equation	Indicators
Evergreen broadleaved forest	Brown, 1997	$\langle ABG \rangle_{est} = \exp(-2.134 + 2.530 \times \ln(\text{DBH}))$	DBH range = 5 – 148 cm, n = 170 trees, R^2 = 0.97
Evergreen broadleaved forest	Chave et al., 2005	$\langle ABG \rangle_{est} = \exp(-2.977 + ln(\rho D^2 H)) \equiv 0.0509 \times \rho D^2 H$	DBH range = 5 – 150 cm, n = 2,410 trees, R^2 = 0.989
Deciduous forest (Dipterocarp)	Basuki et al., 2009	$ln(AGB) = -1.232 + 2.178 \times ln(DBH)$	DBH range = 6 – 200, n = 122 trees, R^2 = 0.992

Chave (2005) collected raw data from tropics to develop models for each forest-type, however, data collected was not tested for Viet Nam. Hence they should assess accuracy and reliability.

Since allometric equations for carbon sequestrated should be broadly applied for the whole area, the accuracy and reliability are particularly considered. Chave et al., (2004) and Brown (1989) pointed that errors of the models have various sources such as errors during tree measurement, sampling plot arrangement, forest status, insufficient number of big trees sampled, diameter intervals, selection of average sample trees in each diameter class, and application of unsuitable models. In addition, accuracy and reliability of biomass models should be assessed not only for individual trees but for forest stands and distribution of tree by diameter classes (Ketterings, 2001).

Using statistical indicators for selecting appropriate models is important to achieve high reliability in the estimates of biomass and carbon. Apart from the popular classic statistical indicators to select the optimal equations (e.g. the highest R^2 with parameters significant at $P < 0.05$), other statistical indicators should be used to ensure the models closest with actual data. Such indicators suggested by Chave (2005), Basuki et al., (2009) are:

- AIC (Akaike Information Criterion) is a measure of the relative fit of a statistical model. The models with smaller AIC algebra are preferred. The AIC is:

$$AIC = n \times \ln\left(\frac{RSS}{n}\right) + 2K \qquad \textbf{Equation 2-5}$$

where, n: number of samples, the RSS: the residual sums of squares, K: parameters of model including the parameter for error estimates (for example, the model y = a + bx, then k = 3).

- Average deviation S% used to evaluate variation between observations and predictions, average deviation. The smaller S% value is preferred:

$$S\% = \frac{100}{n}\sum_{i=1}^{n}\frac{|\mathrm{Yilt} - \mathrm{Yi}|}{\mathrm{Yi}} \qquad \textbf{Equation 2-6}$$

where, Yilt: the predicted biomass; Yi: the observed biomass /carbon; n = number of observations.

The estimate models of tropical forest biomass in parabolic functions of Brown (1997) gave the results S% = 43% - 107%; Chave (2005) reported S% = 52% - 94%. However, using exponential equations of logarithm considerably decreased deviation. Basuki et al., (2009) conducted research in tropical lowland dipterocarp forests published the model with S%, reducing to 26-30 % for all tree species.

- CF (Correction factor): CF is always larger than 1, and a model is preferred when CF reaches 1:

$$CF = \exp(\frac{RSE^2}{2}) \qquad \textbf{Equation 2-7}$$

where, RSE: Residual standard error. The greater the RSE, the greater the CF becomes, indicating low reliability.

2.3 Allometric equations development in Viet Nam

In Viet Nam, equations for estimating forest biomass have taken place in the past, mostly for plantation species, triggered by the onset of the Clean Development Mechanism (CDM), while studies on biomass and equations for biomass estimation of natural forests have been limited.

The first research on forest biomass (plantations) was conducted by Le Hong Phuc (1996) for pine forests in Lam Dong. This research developed models of biomass estimates based on variables of the forest inventory (DBH and H). Ngo Dinh Que (2007) studied the amount of carbon sequestrated in plantations of *Acacia mangium*, *Acacia auriculiformis*, *Acacia* hybrid, *Pinus kesiya* and eucalyptus. A numbers of comprehensive studies on biomass, carbon stock and equations for biomass estimation was then carried out for plantations of *Acacia mangium*, *Acacia hybrid*, *Eucalyptus urophylla*, *mangletia glauca*, *Pinus massoniana*, *Pinus merkusii* by Vu Tan Phuong (2009), Vo Dai Hai et al., (2010), Dang Thinh Trieu (2012) and for *Pinus keysia* by Vu Tan Phuong (2012). Most studies have used DBH and H as predictor variables for biomass estimation. These studies provide estimates for above and below ground biomass of the plantations.

For natural forests, Bao Huy and Pham Tuan Anh (2008), with the support of the World Agroforestry Centre (ICRAF) conducted a preliminary study on CO_2 absorption capacity of the evergreen broadleaf forest in the Central Highlands. The study developed research and analysis methods of natural forest above ground carbon stored in stem, bark, leaves, branches of trees and forest stands. Based on this research, in 2009, research methods of carbon pools in forest ecosystems in Viet Nam were developed (Bao Huy, 2009). In 2012, Bao Huy et al. completed the research of "Defining the amount of CO_2 absorbed by evergreen broad-leaved forests in

the Central Highlands for REDD+". Furthermore, a study on biomass estimation for evergreen broadleaf forests was also carried in Dien Bien under JICA support (Vu Tan Phuong, 2011).

Initial studies on biomass estimation for mangrove forests were also done in the south. These studies developed equations for biomass estimation at tree level for *Avicennia alba*, *Ceriops decandra*, *Rhizophora apiculata*, *Ceriops tagal* (Vien Ngoc Nam, 2010).

Vu Tan Phuong (2006) studied the carbon stock of grass and shrubs of non-forested land (named as status IA, IB in the Viet Namese forests classification system). These became the basis for construction of carbon baselines in CDM plantation projects including for the JICA assisted AR CDM project in Cao Phong district of Hoa Binh province (Pham Xuan Hoan 2008).

As in the above, allometric equations for estimating forest AGB biomass have been developed for some forest types in the tropics, around the world. However, data employed was limited and in most cases, not representative for the different forest types in the tropics including those in Viet Nam. Furthermore, they have not been evaluated on accuracy and reliability, therefore, the possibility for application to Viet Nam is not immediately clear.

Researches for Viet Nam's country-specific allometric equations have taken place as well, but in limited species and forest types. In order to enhance Viet Nam's capacity, and to report its national REDD+ GHG Inventory to the UNFCCC, based on the tier 2 and 3 level of IPCC, further studies for developing country-specific allometric equations are deemed necessary.

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