Estimation of Forest Carbon Densities Using Sample Plots for Development of Forest Reference Level in Vietnam

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Abstract: REDD+ is an international mechanism to reduce emissions and/or enhance removals of greenhouse gases from forest related activities, such as deforestation and forest degradation. To be able to receive result-based payment from REDD+, developing countries need to build and submit to UNFCCC a forest reference level (FRL) with the use of historical forest data. Calculation of carbon densities, together with uncertainties is an important step for development of FRL. In this work, data of 2,098 primary sample plots collected under Cycle IV of the National Forest Inventory, monitoring and assessment programme were verified, corrected and standardized. Based on a new method for screening data and newly developed country-specific allometric equations, carbon densities and their uncertainties were calculated for each forest type per agro-ecological regions. The results of this work are recommended to be utilized to develop national FRL for Vietnam.

Keywords: emission factor, forest carbon density, forest reference level, removal factor, sample plots

1. Introduction

REDD+ is an international mechanism to reduce emissions and/or enhance removals of greenhouse gases from activities related to forest in developing countries. According to Decision no. 1/CP.16, REDD+ include 5 activities: (i) reducing emissions from deforestation, (ii) reducing emissions from forest degradation, (iii) conservation of forest carbon stock, (iv) sustainable management of forest, and (v) enhancement of forest carbon stock. To be able to receive result-based payment from REDD+, developing countries need to build and submit to UNFCCC a forest reference level (FRL) with the use of historical forest data.

Vietnam has a long history of forest inventory, with the most notable one being the National Forest Inventory, Monitoring and Assessment Programme (NFIMAP). This programme has a 5-year cycle and so far, four cycles have been implemented during 1991-2010 by Forest Inventory and Planning Institute (FIPI), with Cycle IV implemented during 2006-2010. In each cycle, a sample plot system was inventoried in order to calculate the growing stock for planning and management purposes. Due to budget constraints, the number of sample plots varied from cycle to cycle, with the number of plots in Cycle IV being 2,098 plots.

According to IPCC, emissions/removals related to forest can be calculated by multiplying activity data (AD) by emissions/removals factors (EF/RFs). EF/RFs can be calculated as the difference between carbon densities of land use type before and after the land use conversion. Previously, two studies were conducted to estimate carbon densities as well as their associated uncertainties (JICA, 2012; FIPI, 2015). Both studies used the plot measurement data from NFIMAP. The first study calculated the carbon densities based on volume equations and default biomass expansion factors and therefore, the uncertainties of the carbon densities were expected to be high. In addition, this study did not estimate the uncertainties of carbon densities ((JICA, 2012).

The second study applied a method for screening the data. Plots with abnormal data were removed from the calculation and as results, only 1,810 out of the 2,098 plots in NFIMAP Cycle IV were used for the calculation. The study estimated the uncertainties associated with the carbon densities but using a formula for simple random sampling while the sampling design of NFIMAP is based on single-stage cluster sampling (FIPI, 2015). These affect the accuracy as well as the transparency of the results of the study.

In addition, after completion of the above two studies, Vietnam has developed a set of country-specific allometric equations for direct estimation of above-ground biomass from plot data by main forest types and agro-ecological regions (UN-REDD, 2015). The application of these equations is expected to reduce the uncertainties of carbon densities for forest types in Vietnam.

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The objective of this study was to re-calculate the carbon densities and their associated uncertainties using: (i) a new method for screening the data of NFIMAP such that all plots are used for the calculation; (ii) newly developed country-specific allometric equations for above-ground biomass calculation; and (iii) a formula for uncertainty estimation based on single-stage cluster sampling.

2. Materials and Method

2.1. Input data

The NFIMAP Cycle IV used a set of primary sample plots (PSPs) which are systematically laid out in a grid of $8 \times 8$ km to collect data for assessing forest growing stock. Only PSPs which were located in forest land were inventoried. The method for establishing and inventorying a PSP is described below.

*Establishment of a PSP*

Each PSP has a size of $1000 \times 1000$ m (horizontal distance) and an area of 100 ha (Figure 1). From the PSP center, two measurement strips are established. The first strip is established from the PSP center to the North direction and contains 20 secondary sample plots (SSPs) indexed from 1 to 20. The second strip is established from the PSP center to the East direction and contains 20 SSPs indexed from 21 to 40. Each strip has a length of 500 m and a width of 20 m. Each SSP has a size of $25 \times 20$ m and an area of 500 m$^2$.

In the case the strips could not be established as regulated above (due to topography features such as rocky mountains, water bodies etc.), an alternative direction of the strips is identified following the rules: (i) In the case the first strip could not be established towards the North direction, the direction is changed to the South, (ii) In the case the second strip could not be established towards the East direction, the direction is changed to the West.

![Figure 1. Layout of a primary sample plot (PSP).](image)
**Method for measuring forest resources**

**a) Trees**

- Natural timber forest or timber-bamboo mixed forest.

- Trees to be measured: All timber trees with diameters at breast height (1.3 m) position (DBH) \( \geq 6 \text{cm} \), within the plot boundary.

- Diameter measurement: Measure DBH in cm for each timber tree. For trees with many stems: If the position of the fork is below 1.3m, measure as two separate trees. Otherwise, measure it as usual.

- Determining species name: Species names should be determined for every tree for which their diameter is measured following the regulations on species names issued by FIPI. For unknown species, tree samples (foliages, flowers and fruits) should be taken for species identification to ensure that \( \geq 90\% \) of the measured trees have their species names identified.

- Determining tree quality: Quality should be determined for each tree that has its DBH measured. Tree quality (only for living trees) is classified into three classes: A (good), B (medium) and C (bad).

- Measuring heights: In each SSP, measure the total height (Hvn) and the bole height of three timber trees nearest to the center position of the plot for which DBH was measured. Only trees with quality A and B are selected for height measurement. Trees with 2 or more stems are not selected for height measurement. The unit for height measurement is meter (m), rounded up to 0.5m.

- Plantation.

  - For plantation having the average DBH \( \geq 6 \text{cm} \): For trees with DBH \( \geq 6 \text{cm} \), measure as in timber forest. For trees with DBH \( < 6 \text{cm} \), only determine tree species and count the total number of trees in the secondary sample plot (500m\(^2\)), observe the average diameter and height and fill in the field form.

  - For plantation with the average DBH \( < 6 \text{cm} \): Only determine tree species and count the total number of trees in the right half of SSPs. For each tree species measure the total heights of three normal trees nearest to the plot center.

- Non-forest land.

  - Conduct the measurement as with natural timber forest regardless of tree species and use (including trees for wood, fruit trees and industrial trees).

  - Measure the total height and bole height of all trees for which their DBH was measured.

  - In the case a tree has a fork below the 1.3 m level but its stem has a special shape which makes it difficult to determine the number of stems, measure the DBH at the position right below the fork.

**b) Bamboo**

Only measure bamboo in the area of 100 m\(^2\) (10 m \( \times \) 10 m) located at the far-left corner of each SSP (striped parts in Figure 2), regardless of the origin being natural or planted. In each bamboo measurement plot, select only one normally-growing stem for measuring DBH and Hvn (from the base to the position having diameter of 1.0 cm). The following cases should be distinguished:

1. Bamboo growing scattered: Determine the bamboo species name and count the number of stems by three age classes: young-aged, medium-aged, and old-aged based on the following features:
+ Young-aged class: bamboos with age of 1-2 years old and are in adequate 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 colour 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; 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 colour of stem and main branches skin is deep blue mixed with brownish yellow and there is spotted lichen on the stem.

+ Old-aged 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 blue and stems are bluish yellow or spotted whitish grey caused by strong development of lichen (70-80%) and the deep blue colour for stem skin almost disappears.

(2) Bamboo growing in clump: Determine the species and the number of clumps in the measurement area, select one representative clump and count the number of stems by three age classes (young, medium-aged and old). Clumps lie on the boundary are treated as follows: If more than half of the clump is inside the measurement area, treat this clump as it is in the measurement area. Otherwise, treat this clump as it is outside the measurement area.

![Figure 2. Layout of bamboo measurement plots in SSPs.](image)

2.2. Method for verification, correction of standardization of data

Sample plots data of NFIMAP cycle IV are verified, corrected and standardized as follows:

a) Removal of duplicated records
In the database of NFIMAP cycle IV, there are records being inputted multiple times (these records have the same PSP name, SSP name and tree index). The “Pivot Table” function in Excel was used to identify these records. If the duplicate records has the same data, only one record would be kept. Otherwise, the field notes would be checked to keep the correct record.
b) Addition of missing records
In some SSPs, there are potential of missing records (for example, trees index number 4 and 6 were recorded but tree index 5 was missing). These potential missing records were checked against the field notes. If these records existed in the field notes, their data would be added to the database.

c) Additional input of missing SSPs
There are some SSPs of forest types but have no tree or bamboo data in the database. These SSPs were identified and their field notes were checked. If their field notes had data, they would be entered to the database.

d) Verification and correction of data on Hvn and bole height
Trees with Hvn measurements should also have had bole height measured. Trees with Hvn smaller than bole height (potential typographical errors) were scanned and checked against field notes to correct the data as appropriate. Trees with unrealistic Hvn (higher than 60 m) were also identified and corrected with the field notes.

e) Verification and correction of DBH and Hvn of trees
- Develop the height curves and identify outlier trees; check with their field notes to correct if errors exist.

Method to identify outlier trees are as follows:

Using the logarithm function with error following the normal distribution and the variance being the power function of DBH as follows:

$$H_{vn} = a + b \cdot \ln(DBH) + N(0, DBH^k)$$

Applying regression analysis to identify the optimal values $A$, $B$, and $K$ for the height curve. Then, develop two height curves $H1$ and $H2$ as follows:

$$H1 = A + B \cdot \ln(DBH) + 5 \times DBH^K$$

$$H2 = A + B \cdot \ln(DBH) - 5 \times DBH^K$$

Figure 3. Method for determine trees with abnormal DBH-Hvn correlation.
Trees that have their total heights above the H1 curve (in red) or below the H2 curve (in green) in Figure 3 are identified as outliers.

**f) Correction of misspelled species names as necessary and assigning scientific names for each records**

Tree species in NFIMAP plot data are in Vietnamese and have many misspelled errors. To assign wood densities (ratio of dry mass to fresh volume, WD) for tree species using the Global Wood density database (Chave et al., 2009), scientific names are needed. Therefore, the Vietnamese species names were corrected and assigned scientific names using the species name database developed by FIPI.

**g) Assignment of WD for each species**

WD is associated to each species based on 1,300 WD measurements collected in Vietnam by the Vietnam Forestry University, the Vietnamese Academy of Forest Science and the Tay Nguyen University and completed by the Global Wood density database (Chave et al., 2009). WDs were not available for all the species. Therefore, for each species identified in the NFIMAP cycle IV data, WD was selected with the following hierarchy of preference: 1) species average in the Vietnamese database, 2) species average in the Global Wood Density database, 3) average at genus level in the Vietnamese database, 4) average at genus level in the Global Wood Density database, and 5) national average of the Vietnamese database: 0.584 g/cm$^3$.

**h) Assignment of forest and land use types for SSPs**

Each SSP was originally assigned a field land-use code according the Regulation No. 84 (Ministry of Forestry, 1984). However, the forest cover maps used to generate AD apply a classification system of 17 forest and land use types based on Circular No. 34 (MARD, 2009) as described in Table 1. Therefore, there is a need to assign the forest and land use type for each SSP following the classification system used for generating AD.

**Table 1. The forest and land use classification system applied in forest cover maps.**

| Code | Forest and land use type               | Forest/Non-forest |
|------|---------------------------------------|-------------------|
| 1    | Evergreen broadleaf - rich            | Forest            |
| 2    | Evergreen broadleaf - medium          | Forest            |
| 3    | Evergreen broadleaf - poor            | Forest            |
| 4    | Evergreen broadleaf - regrowth        | Forest            |
| 5    | Deciduous                             | Forest            |
| 6    | Bamboo                                | Forest            |
| 7    | Mixed woody - bamboo                  | Forest            |
| 8    | Coniferous                            | Forest            |
| 9    | Mixed broadleaf - coniferous          | Forest            |
| 10   | Mangroves                             | Forest            |
| 11   | Limestone forest                      | Forest            |
| 12   | Plantations                           | Forest            |
| 13   | Limestone without forest              | Non-forest        |
| 14   | Bared land                            | Non-forest        |
| 15   | Water bodies                          | Non-forest        |
| 16   | Residence                             | Non-forest        |
| 17   | Other land                            | Non-forest        |

The following steps were applied:

i. Use expert knowledge to create a look-up table between forest and land use types in Regulation No. 84 and the ones in Circular No. 34.

ii. Use this look-up table to assign a temporary forest and land use types for each SSP.

iii. Calculate parameters such as average number of trees per hectare (N/ha), average number of bamboos per hectare (T/ha), average DBH, average volume per hectare (m$^3$/ha) and species composition for each SSP.
iv. Based on the above parameters and in combination with the temporary forest and land use
types of the SSP and surrounding SSPs, assign new forest and land use class for the SSP as
necessary. This step is conducted by experienced forest inventory experts.

2.3. Method for calculation of average carbon density for each forest type

To reduce the uncertainty of the emission and removal estimates, Vietnam will estimate EF/RFs
by agro-ecological regions. Therefore, the next step is to estimate carbon density for each forest
type by agro-ecological region. There are eight agro-ecological regions in Vietnam, namely: North-
east, Northwest, Red River Delta, North Central Coast, South Central Coast, Central Highlands,
Southeast, and Mekong River Delta (Figure 4). Since the number of PSPs in the Red River Delta is
not large enough, this region was combined with the Northeast region for the estimation of average
carbon density. For the same reason, the Mekong River Delta was combined with the Southeast
region for calculation of average carbon density. It is noted that the forest cover in these two regions
is very small compared to the other regions.

Figure 4. The eight agro-ecological regions in Vietnam.

2.3.1. Calculation of biomass for individual trees and bamboo

In this section, tree DBH is expressed in cm, Hvn in m, WD in g/cm$^3$, volume (V) in m$^3$ and
above-ground biomass (AGB) in kg.

a) Trees

Step 1: Construction of height curve (DBH-Hvn correlation equation)

From the input data, a DBH-Hvn correlation equation per agro-ecological region was developed.
The logarithm function is chosen as the DBH-Hvn correlation model:

\[ Hvn = a + b \cdot \ln(DBH) \]

Where a and b are the coefficients of the equation. Their optimal values can be found by using a
regression method. A regression analysis is applied with non-linear mixed effects on forest types
(Table 2) to find the optimal values for these parameters. In this work, the regression is conducted
by a script written in the statistical software R (version 3.2.3) which uses the nlme() function. The
R script is given below:
Table 2. Classification of sub-forest types for development of height curves using non-linear mixed effects models

| Forest and land use type                        | Code for mixed effects |
|------------------------------------------------|------------------------|
| Evergreen broadleaf, Bamboo, Mixed timber      | 1                      |
| - bamboo, Bare land, Non-forest land           |                        |
| Deciduous                                      | 2                      |
| Coniferous, Mixed broadleaf □ coniferous       | 3                      |
| Mangrove                                       | 4                      |
| Plantation                                     | 5                      |

Step 2: Calculation of Hv$n$ for trees without height measurement
The developed height curves is applied to calculate Hv$n$ for other trees that do not have their total heights measured.

Step 3: Calculation of tree length (H$mt$) for each individual tree
The tree heights used in allometric equations are in fact the length of the tree stems (H$mt$, in m), which is calculated from the Hv$n$ using the following equation (FIPI, 1995):

\[ H_{mt} = H_{vn} \times 1.04 \]

Step 4: Calculation of AGB for individual tree
- *Evergreen broadleaf forests, bamboo forests, mixed timber □ bamboo forests*

Country-specific allometric equation (UN-REDD, 2015) with 3 predictors (DBH, H$mt$ and WD) were used to estimate the AGB for each individual tree. The equation applied is:

\[ AGB = 0.757 \times (DBH^2 \times H_{mt} \times WD/10)^{0.930} \]

- *Deciduous forest*

Country-specific allometric equations (UN-REDD, 2015) with two predictors (DBH and H$mt$) were applied to estimate AGB of each individual tree. The equation applied is:
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[7] \( AGB = 310.3 \times (DBH^2 \times Hmt/10000) \)

- **Natural coniferous forest**

Since no allometric biomass equation specific to Vietnam natural coniferous forest is available, the indirect method of calculation using tree volume is applied as follows:

[8] \( V = 0.744 \times DBH^{1.9909} \times Hmt^{0.7814} \times 10^{-4} \)

[9] \( AGB = V \times BEF \times WD \)

Where BEF is the biomass expansion factor. Since the tree volume used in Vietnam is not the merchantable volume, the default BEF value provided in IPCC guidelines is considered not appropriate. In this study, the BEF of 1.3 (Brown, 1997) and the WD of 0.5 g/cm³ are used for coniferous forests.

- **Mangrove forest**

Since NFIMAP Cycle IV has very few number of SSPs located in mangrove forest, the carbon density of this forest type was not calculated in this work.

- **Plantation**

There are many species of plantation in Vietnam. Therefore, for simplification, the calculation method for plantation was applied as follows: For Pinus spp. plantations, the same calculation method for the natural coniferous forest is applied; for other plantations, the same calculation method as with evergreen broadleaf forests is applied.

b) **Bamboo**

Country-specific allometric equations for estimating AGB of four main bamboo species (Lo o, Luong, Nua and Vau) have been developed (UN-REDD, 2015). The allometric equations for these four species are given below:

- **Lo o** (*Bambusa procera*):

[10] \( AGB = 0.0612 \times DBH^{2.0848} \times Hvn^{0.2779} \)

- **Luong** (*Dendrocalamus membranaceus*):

[11] \( AGB = 0.1013 \times DBH^{1.9667} \times Hvn^{0.2779} \)

- **Nua** (*Bambusa chirostachyoides*):

[12] \( AGB = 0.3558 \times DBH^{1.2155} \times Hvn^{0.2779} \)

- **Vau** (*Indosasa angustata*):

[13] \( AGB = 0.2829 \times DBH^{1.4307} \times Hvn^{0.2779} \)

For other bamboo species, AGB can be approximated by applying one of the above four equations. Table 3 shows the equations which were applied to other bamboo species:
Table 3. Equations applied for bamboo species without species-specific equations.

| No | Bamboo species | Equation applied |
|----|----------------|-----------------|
| 1  | Buong Luong    |                 |
| 2  | Dung Nua       |                 |
| 3  | Giang Nua      |                 |
| 4  | Hoc Luong      |                 |
| 5  | Hop Luong      |                 |
| 6  | Le Lo o        |                 |
| 7  | Lung Nua       |                 |
| 8  | Mai Luong      |                 |
| 9  | May song Nua   |                 |
| 10 | Met Luong      |                 |
| 11 | Mum Lo o       |                 |
| 12 | Roc Luong      |                 |
| 13 | Tre Luong      |                 |
| 14 | Truc Vau       |                 |

2.3.2. Estimation of carbon stock of SSPs

Step 1: Estimating AGB of SSP
Total AGB of trees in each SSP is estimated as the sum of all individual tree AGBs in this SSP.

\[ AGB_{Ti} = \sum_{j=1}^{n_i} AGB_{Tij} \]

Where \( AGB_{Ti} \) is the total AGB of trees in SSP \( i \), \( n_i \) is the number of trees in SSP \( i \), and \( AGB_{Tij} \) is the AGB of the \( j^{th} \) tree in SSP \( i \).

Total AGB of bamboos in each SSP is estimated as the sum of all individual bamboo AGBs in this SSP.

\[ AGB_{Bi} = \sum_{j=1}^{m_i} AGB_{Bij} \]

Where \( AGB_{Bi} \) is the total AGB of bamboos in SSP \( i \), \( m_i \) is the number of bamboos in SSP \( i \), and \( AGB_{Bij} \) is the AGB of the \( j^{th} \) bamboo in SSP \( i \).

Since the area of tree measurement in each SSP is 500 m\(^2\) and the area of bamboo measurement in each SSP is 100 m\(^2\), the total AGB of both trees and bamboos in SSP \( i \), \( AGB_i \), is:

\[ AGB_i = AGB_{Ti} + 5 \times AGB_{Bi} \]

The AGB for each SSP is in the unit of kg per 500 m\(^2\). The following formula is applied to convert the unit to tons per ha:

\[ tAGB_{ha} = AGB_i \times \frac{10000}{500 \times 1000} = AGB_i/50 \]

Step 2: Estimating below-ground biomass (BGB) of SSP.
BGB is estimated for each SSP as follows:

\[ tBGB_{ha} = tAGB_{ha} \times R \]

Where \( tBGB_{ha} \) is the BGB of SSP \( i \) in the unit of tons per ha; \( R \) is the root-to-shoot ratio. In this work, the values proposed by Mokany et al. (2006) for \( R \), which is 0.205 for SSPs with \( tAGB_{ha} < 125 \) ton/ha or 0.235 for SSPs with \( tAGB_{ha} \geq 125 \) ton/ha, are applied.
Step 3: Estimate total living biomass (including AGB and BGB) for each SSP.
Total living biomass in SSP \(i\) is the sum of AGB and BGB of this SSP:

\[
t_{B_i} = t_{AGB, i} + t_{BGB, i}
\]

Step 4: Estimating carbon stock of each SSP.
Carbon stock of SSP \(i\) in tons of carbon per ha, \(t_{C, i}\), is calculated as follows:

\[
t_{C, i} = t_{B_i} \times CF
\]

Where \(t_{B, i}\) is total living biomass of SSP \(i\) in tons per ha; \(CF\) is the carbon fraction coefficient.
This work applied the IPCC default value for \(CF\), which is 0.47 (IPCC, 2006).

2.3.3. Estimation of carbon density for each forest type

The carbon density of forest type \(i\), \(t_{C, i}\), is calculated as the mean of the carbon stock per ha over all SSPs in this forest type.

\[
t_{C, i} = \frac{1}{n_{p, i}} \sum_{j=1}^{n_{p, i}} t_{C, i, j}
\]

Where \(n_{p, i}\) is the number of SSPs in forest type \(i\); \(t_{C, i, j}\) is the carbon stock per ha of SSP \(j\) in forest type \(i\).

2.3.4. Calculation of errors for carbon densities

Step 1: Calculation of coefficient of variation.
The coefficient of variation of carbon density in forest type \(i\) is estimated by the formula below:

\[
CV\%_i = \frac{SD_i}{t_{C, i}} \times 100 = \frac{SE_i \times \sqrt{t_i}}{t_{C, i}} \times 100
\]

Where \(SD_i\) and \(SE_i\) are, respectively, the standard deviation and standard error of carbon density in forest type \(i\); \(l_i\) is the number of PSPs with at least one SSP in forest type \(i\). Since the sampling design in NFIMAP is based on a grid of PSPs distributed systematically with each PSP is a cluster of 40 SSPs, the sampling unit is a PSP. Therefore, the standard error is estimated by the equation below (adapted from equation 2.12 in Dahm (2006)):

\[
SE_i = \frac{1}{\sum_{j=1}^{l_i} n_{p, ij}} \sqrt{\frac{l_i - 1}{n_{p, ij}}} \sum_{j=1}^{l_i} (Y_{ij} - t_{C, i})^2
\]

Where \(Y_{ij}\) is the sum of \(t_{C, i}\) in all SSPs of forest type \(i\) in PSP \(j\); \(n_{p, ij}\) is the number of SSPs of forest type \(i\) in PSP \(j\).

Step 2: Calculation of errors.
Error in percentage of carbon density for forest type \(i\), \(E\%_i\), is calculated by the following formula:

\[
E\%_i = \frac{t_{a, l_i - 1} \times CV\%_i}{\sqrt{t_i}}
\]

Where \(t_{a, l_i - 1}\) is the value of the \(t\) distribution of \(l_i - 1\) degrees of freedom with a confidence interval (CI) of \(1 - \alpha\). In this work, errors are estimated at the 95% CI (\(\alpha = 0.05\)).
3. Results and Discussion

3.1. Verification, correction and standardization of NFIMAP Cycle IV data

Among the 1,192,573 tree records, the process of verifying and correcting the sample plot data of NFIMAP Cycle IV, led to the following results:

- Removal of approximately 1,000 duplicated records;
- Addition of approximately 400 new records in SSPs already present in the database;
- Addition of plot data for 25 new SSPs;
- Revision of data (species name, DBH, total height, stem height, number of trees) for approximately 1,200 records.

In total, 759 species were identified in sample plot data of NFIMAP Cycle IV. In terms of number of species, 55% of the species had a wood density value available at species or genus level in the Vietnamese database and only 10% of the species were attributed to a default global average.

3.2. Calculation of carbon densities and associated errors for each forest type per agro-ecological regions

Carbon densities and associated uncertainties (i.e., errors at the 95% CI) for each forest type per agro-ecological regions and at the national level are given in Tables 4 to 10 (only forest types present in each region are listed).

Table 4. Carbon densities (tC/ha) per forest types in the Northwest region.

| Forest type code | # of PSP | # of SSP | Average C stock (tC/ha) | Coefficient of variation (%) | Uncertainty (%) |
|------------------|---------|---------|-------------------------|-----------------------------|----------------|
| 1                | 8       | 125     | 145.01                  | 56.36                       | 47.12          |
| 2                | 22      | 273     | 64.63                   | 18.17                       | 8.06           |
| 3                | 34      | 350     | 28.19                   | 69.86                       | 24.37          |
| 4                | 92      | 1,269   | 17.28                   | 65.86                       | 13.64          |
| 6                | 26      | 306     | 15.67                   | 77.13                       | 31.15          |
| 7                | 24      | 238     | 29.64                   | 49.17                       | 20.76          |
| 11               | 2       | 19      | 13.54                   | 103.26                      | 927.77         |
| 12               | 11      | 83      | 11.86                   | 54.18                       | 36.40          |

Table 5. Carbon densities (tC/ha) per forest types in the Northeast and Red River Delta regions.

| Forest type code | # of PSP | # of SSP | Average C stock (tC/ha) | Coefficient of variation (%) | Uncertainty (%) |
|------------------|---------|---------|-------------------------|-----------------------------|----------------|
| 1                | 9       | 47      | 106.63                  | 15.35                       | 11.80          |
| 2                | 36      | 224     | 64.11                   | 17.14                       | 5.80           |
| 3                | 64      | 532     | 20.07                   | 48.59                       | 12.14          |
| 4                | 224     | 3,294   | 16.33                   | 72.34                       | 9.53           |
| 6                | 65      | 639     | 17.27                   | 69.69                       | 17.27          |
| 7                | 114     | 1,382   | 27.31                   | 54.11                       | 10.04          |
| 8                | 1       | 14      | 118.59                  | Na                          | Na             |
| 9                | 1       | 23      | 27.08                   | Na                          | Na             |
| 11               | 3       | 15      | 11.59                   | 52.00                       | 129.18         |
| 12               | 139     | 1,710   | 14.40                   | 92.39                       | 15.49          |

From the above tables, it can be observed that carbon densities of each forest types vary largely across agro-ecological regions, especially for evergreen broadleaf (EGBL) rich forest. The smallest and largest carbon densities for this forest type are 106.63 tC/ha (Northeast and Red River Delta) and 161.44 tC/ha (Southeast and Mekong River Delta) with the national average of 139.86 tC/ha (Figure 5). This emphasis that the stratification to agro-ecological regions for calculation of carbon stocks is appropriate.
Table 6. Carbon densities (tC/ha) per forest types in the North Central Coast region.

| Forest type code | # of PSP | # of SSP | Average C stock (tC/ha) | Coefficient of variation (%) | Uncertainty (%) |
|------------------|---------|---------|------------------------|-------------------------------|----------------|
| 1                | 78      | 1,225   | 141.18                 | 41.95                         | 9.46           |
| 2                | 172     | 2,398   | 70.24                  | 17.45                         | 2.63           |
| 3                | 185     | 2,481   | 31.04                  | 28.66                         | 4.16           |
| 4                | 155     | 1,663   | 19.21                  | 110.99                        | 17.61          |
| 6                | 96      | 1,463   | 14.74                  | 88.77                         | 17.99          |
| 7                | 91      | 1,131   | 39.67                  | 54.85                         | 11.42          |
| 11               | 2       | 11      | 38.21                  | 31.89                         | 286.51         |
| 12               | 42      | 444     | 22.14                  | 96.91                         | 29.89          |

Table 7. Carbon densities (tC/ha) per forest types in the South Central Coast region.

| Forest type code | # of PSP | # of SSP | Average C stock (tC/ha) | Coefficient of variation (%) | Uncertainty (%) |
|------------------|---------|---------|------------------------|-------------------------------|----------------|
| 1                | 87      | 1,341   | 133.92                 | 28.42                         | 6.06           |
| 2                | 148     | 2,132   | 75.64                  | 19.96                         | 3.24           |
| 3                | 140     | 1,572   | 32.49                  | 32.83                         | 5.49           |
| 4                | 160     | 2,461   | 27.48                  | 80.77                         | 12.61          |
| 5                | 41      | 1,163   | 28.35                  | 67.24                         | 21.25          |
| 6                | 17      | 115     | 13.21                  | 52.41                         | 20.95          |
| 7                | 41      | 529     | 50.44                  | 71.92                         | 22.70          |
| 8                | 1       | 40      | 91.17                  | Na                            | Na             |
| 9                | 2       | 32      | 39.54                  | 7.22                          | 64.85          |
| 12               | 30      | 298     | 10.41                  | 61.70                         | 23.04          |

Table 8. Carbon densities (tC/ha) per forest types in the Central Highlands region.

| Forest type code | # of PSP | # of SSP | Average C stock (tC/ha) | Coefficient of variation (%) | Uncertainty (%) |
|------------------|---------|---------|------------------------|-------------------------------|----------------|
| 1                | 299     | 3,095   | 141.26                 | 21.66                         | 2.95           |
| 2                | 306     | 3,537   | 79.39                  | 14.62                         | 1.64           |
| 3                | 238     | 1,698   | 37.67                  | 28.52                         | 3.64           |
| 4                | 221     | 2,748   | 43.21                  | 60.26                         | 7.99           |
| 5                | 124     | 3,238   | 32.22                  | 44.87                         | 7.98           |
| 6                | 78      | 819     | 11.72                  | 120.39                        | 27.14          |
| 7                | 142     | 2,012   | 50.82                  | 67.22                         | 11.15          |
| 8                | 34      | 591     | 94.50                  | 33.65                         | 11.74          |
| 9                | 16      | 172     | 76.97                  | 90.40                         | 48.17          |
| 12               | 32      | 371     | 23.27                  | 116.94                        | 42.16          |

Table 9. Carbon densities (tC/ha) per forest types in the Southeast and Mekong River Delta regions.

| Forest type code | # of PSP | # of SSP | Average C stock (tC/ha) | Coefficient of variation (%) | Uncertainty (%) |
|------------------|---------|---------|------------------------|-------------------------------|----------------|
| 1                | 12      | 137     | 161.44                 | 25.64                         | 16.29          |
| 2                | 24      | 255     | 82.38                  | 19.12                         | 8.08           |
| 3                | 28      | 227     | 34.16                  | 44.61                         | 17.30          |
| 4                | 11      | 314     | 51.91                  | 27.68                         | 18.59          |
| 6                | 11      | 75      | 16.32                  | 120.82                        | 81.17          |
| 7                | 17      | 293     | 56.11                  | 52.11                         | 26.79          |
| 12               | 15      | 305     | 15.09                  | 51.59                         | 28.57          |
Table 10. Carbon densities (tC/ha) per forest types at the national level.

| Forest type code | # of PSP | # of SSP | Average C stock (tC/ha) | Coefficient of variation (%) | Uncertainty (%) |
|------------------|----------|----------|-------------------------|-------------------------------|-----------------|
| 1                | 403      | 5,970    | 139.86                  | 30.22                         | 2.96            |
| 2                | 708      | 8,819    | 75.24                   | 18.88                         | 1.39            |
| 3                | 689      | 6,860    | 32.12                   | 38.54                         | 2.88            |
| 4                | 863      | 11,749   | 26.41                   | 93.23                         | 6.23            |
| 5                | 165      | 4,401    | 31.20                   | 50.99                         | 7.84            |
| 6                | 293      | 3,417    | 14.56                   | 92.58                         | 10.64           |
| 7                | 429      | 5,585    | 42.08                   | 74.03                         | 7.03            |
| 8                | 36       | 645      | 94.82                   | 31.78                         | 10.75           |
| 9                | 19       | 227      | 66.64                   | 92.84                         | 44.75           |
| 11               | 7        | 45       | 18.92                   | 89.77                         | 83.02           |
| 12               | 269      | 3,211    | 16.12                   | 105.28                        | 12.64           |

Figure 5. Carbon densities of EGBL rich forest by agro-ecological regions. (CH: Central Highlands; NCC: North Central Coast; NE: Northeast and Red River Delta; NW: Northwest; SCC: South Central Coast; SE: Southeast and Mekong River Delta)
Another observation is that forest types with large coefficient of variation include: EGBL - regrowth forest (code 4), bamboo forest (6), mixed timber-bamboo forest (7), mixed broadleaf-coniferous forest (9), limestone forest (11) and plantation (12). The main reason may be that, unlike the forest types (1) through (3), these forest types are not classified by stocking level.

4. Conclusion and Future Works

Development of FRL to submit to UNFCCC is a requirement for developing countries to receive result-based payment from implementing REDD+ activities. In this work, sample plots data of 2,098 PSPs collected under Cycle IV of NFIMAP have been verified, corrected and standardized. Based on these improved data and allometric equations developed specifically for Vietnam, carbon densities and associated uncertainties (errors at the 95% CI) were calculated for forest types per agro-ecological regions. These results are recommended to be utilized for development of national FRL for Vietnam.

In this work, only carbon in AGB and BGB were accounted for. Carbon in other pools such as dead wood, litter and soils are still excluded from the calculation of carbon densities. In future works, carbon in dead wood and litter will be examined, and included in the calculation to increase the completeness and reduce the uncertainty of the FRL.

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