INBAR Technical Report

A Manual for Bamboo Forest Biomass and Carbon Assessment

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INBAR
INTERNATIONAL BAMBOO AND RATTAN ORGANISATION

CGIAR
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The International Bamboo and Rattan Organisation

The International Bamboo and Rattan Organisation, INBAR, is an intergovernmental organisation bringing together 45 Member States to promote the use of bamboo and rattan for sustainable development.

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ACRONYMS AND ABBREVIATIONS

A	Age of bamboo culm
AGB	Above-ground biomass
AGB_{bamboo}	Above-ground biomass of bamboo plant
AGB_{clump}	Above-ground biomass of bamboo clump
$AGB_{non\text{-}bamboo}$	Above-ground biomass of non-bamboo vegetation
AGC	Above-ground carbon
$AGCO_2$	Above-ground CO_2
AIC	Akaike Information Criterion
B_{br}	Biomass of bamboo branches
$B_{br\text{-}clump}$	Biomass of bamboo branches per clump
B_{co}	Biomass of coarse roots
$B_{co\text{-}clump}$	Clump biomass of coarse roots
B_{cu}	Biomass of bamboo culm
$B_{cu\text{-}clump}$	Biomass of bamboo culms per clump
B_{fi}	Biomass of fine roots
$B_{fi\text{-}clump}$	Clump biomass of fine roots
BGB	Below-ground biomass
BGB_{bamboo}	Below-ground biomass of bamboo plant
BGB_{clump}	Below-ground biomass of bamboo clump
BGB_{co}	Below-ground biomass of bamboo plant coarse roots
BGB_{fi}	Below-ground biomass of bamboo plant fine roots
$BGB_{non\text{-}bamboo}$	Below-ground biomass of non-bamboo vegetation
BGB_{rh}	Below-ground biomass of bamboo plant rhizomes
BGC	Below-ground carbon
$BGCO_2$	Below-ground CO_2
B_{le}	Biomass of bamboo leaves
$B_{le\text{-}clump}$	Biomass of bamboo leaves per clump
B_{li}	Biomass in litter
$B_{li}ha^{-1}$	biomass in litter per hectare
B_{rh}	Biomass of rhizomes
$B_{rh\text{-}clump}$	Clump biomass of rhizomes

CA	Crown area
CD	Crown diameter
C_{li}	Carbon in litter
CO_{2li}	CO_2 in litter
D	Diameter at breast height
D_0	Diameter at the base of plant, at the root collar
D_{clump}	Diameter at breast height of bamboo clump
DME	Distance Measuring Equipment
FI	Fit Index
FurI	Furnival Index
G_{clump}	Girth at breast height of bamboo clump
GHG	Greenhouse gas
GIS	Geographical Information System
H	Height of plant, bamboo
H_{clump}	Height of bamboo clump
IPCC	Intergovernmental Panel on Climate Change
LD	Litter Depth
MAPE	Mean Absolute Percent Error
N_{clump}	Number of clumps per unit area
N_{culm}	Number of culms per clump
QA	Quality Assurance
QC	Quality Control
RMSE	Root Mean Squared Error
RS	Remote Sensing
RSR	Root-Shoot Ratio: Ratio of BGB to AGB
SAS	Statistical Analysis System
SOC	Soil Organic Carbon
SUR	Seemingly Unrelated Regression
TB	Total biomass including AGB + BGB + B_{li}
TB_{bamboo}	Total bamboo plant biomass TB_{bamboo} = Bcu +Bbr + Ble + BGB_{bamboo} = AGB_{bamboo} + BGB_{bamboo}
TC	Total carbon including AGC + BGC + C_{li}
TCO_2	Total CO_2 including $AGCO_2$ + $BGCO_2$+ CO_{2li}
UN-REDD	United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries

GLOSSARY

Bamboo plant	Consists of a culm, branches and leaves above the ground and a rhizome and roots below the ground.
Carbon Content	Absolute amount of carbon in a pool or parts of it (IPCC, 2006)
Carbon Fraction (CF)	Tonne of carbon per tonne of biomass dry matter (IPCC, 2006) Default value = 0.47
Carbon Pool	A reservoir of carbon; a system that has the capacity to accumulate or release carbon (IPCC, 2003).
Carbon Sequestration (uptake)	The process of increasing the carbon content of a carbon pool other than the atmosphere (IPCC, 2003).
Carbon Sink	Any process or mechanism that removes a GHG, an aerosol or a precursor of a GHG from the atmosphere. A given pool (reservoir) can be a sink for atmospheric carbon if, during a given interval, more carbon is flowing into it than is flowing out (IPCC, 2003).
Carbon Stock	The absolute quantity of carbon held within a pool at a specified time. The unit of measurement is mass (IPCC, 2003).
Carbon Stock Change	The carbon stock in a pool changes due to gains and losses. When losses exceed gains, the stock decreases and the pool acts as a source; when gains exceed losses, the pools accumulate carbon and the pools act as a sink (IPCC, 2006).

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PREFACE

Bamboo covers over 30 million hectares (ha) across the tropical and subtropical regions of the world and has enormous potential for socio-economic development and environmental protection. In many parts of the world, bamboo has proven to play a significant role in poverty alleviation, job creation and economic development as well as being a cultural symbol. Bamboos are very effective plants in controlling soil erosion, regulating water and reducing flood damage and they have huge potential for mitigating climate change through storing a significant amount of carbon in the bamboo forest ecosystem and sequestering carbon from the atmosphere. Bamboos are amongst the fastest growing plants in the world. With careful management and selective harvesting, the annual rate of carbon sequestration of many bamboo forests can be higher than the fast-growing tree forests. Therefore, understanding the dynamics of carbon cycle in the bamboo forest ecosystem is critically important for helping us make the best use of bamboo for climate change mitigation and economic development.

There are many international guidelines for forest carbon assessment, including guidelines by the Intergovernmental Panel on Climate Change (IPCC) on national greenhouse gas (GHG) inventory. These guidelines provide very specific details for measuring tree species but not for bamboos. When it comes to measuring biomass and carbon, bamboos are different from trees, mainly because bamboos are hollow inside, and the correlation between the diameter or the diameter and height of the bamboo culm with bamboo biomass or net bamboo volume largely depends on culm age, bamboo species and site condition. Furthermore, many clumping bamboo species have very dense culms, which makes it impossible for surveyors to measure the diameter of the culms. Therefore, it is important to have international standard guidelines for bamboo biomass and carbon assessment. The guidelines in this book have been developed according to the required international standards and provide clear instructions for technical staff who conduct bamboo forest inventory and bamboo carbon assessment.

This manual comprises four chapters. Chapter I provides basic information on bamboo and the concepts of carbon pools in the bamboo forest, which are used to unify the understandings of the concepts. Chapter II provides an overview of the methodology that can be used to measure three major carbon pools of bamboo forest, including above-ground, below-ground and litter biomass (B_{li}). This chapter also offers guidelines on how to build and evaluate allometric models of estimating bamboo biomass and carbon. The manual is meant for people who hold a minimal degree in forestry and forest environment; the guidelines are expected to help these people develop allometric equations and conduct validation of the allometric equations. Chapter III offers step-by-step instructions of how to collect data in the field in order to prepare the data set for estimating bamboo stocks, biomass and carbon of bamboo forests. The various measurement methods are introduced, and users can choose the most appropriate method in accordance with the circumstances. Chapter IV offers specific guidance on how to use the models introduced in Chapter II and the data gathered in Chapter III for estimating bamboo stocks, biomass and carbon as well as ways to report CO_2 emissions or removals in bamboo forests.

To compile this manual, the authors have made considerable effort to aggregate the methods and technological advances in bamboo forest inventory and biometric sciences. It is hoped that this manual will make positive contributions to the measurement and assessment of biomass and carbon as well as to sustainable bamboo forest management.

Authors

Chapter I. INTRODUCTION: BAMBOO FOREST AND ITS BIOMASS AND CARBON

1. The general biological and ecological characteristics of bamboo

Bamboo is a plant that belongs to the true grass family *Poaceae*, a subfamily of *Bambusoideae*; it is commonly known as 'poor man's timber' and is used by many rural populations in daily life (Goyal et al, 2012). There are over 1600 bamboo species globally, consisting of 75-107 genera worldwide. Bamboo forests are distributed in approximately 31.5 million hectares (ha) of forested area, mostly in Brazil, China and India (Yuen, Fung and Ziegler, 2017; Kaushal et al, 2018). Bamboo matures in 3-5 years and thereafter can be harvested annually for about 20 years (Tariyal, 2016; Dalagnol et al, 2018) or longer, depending on the gregarious flowering period, after which bamboo dies. The bamboo gregarious flowering interval can be between 20 and 120 years, depending on the species.

Bamboos are naturally distributed in tropical and subtropical belts between latitudes around 46° north and 47° south and are commonly found in Africa, Asia and Central and South America. Some species can also successfully grow in the temperate regions of Europe and North America (Lobovikov et al, 2007). One per cent of the world's natural forests is dominated by the bamboo forests (Dalagnol et al, 2018). There are 52 countries and islands with the highest number of bamboo species (Canavan et al, 2017), of which the three top countries include Brazil, China and India.

Bamboo is a diverse plant that easily adapts to different site conditions (Lobovikov et al, 2007). It can grow in a wide variety of soil types, ranging from organic poor to mineral rich and from drought to flooding conditions. Bamboo can grow rapidly in hot and humid rainforests and even in cold climates with temperatures around -20°C (Goyal et al, 2012).

Bamboo is one of the most important non-timber forest products in natural forests or in non-forestry areas. It is widely distributed and highly capable of natural regeneration (Yiping et al, 2010; Li, Lin and Yen, 2016; Zhou et al, 2011; Canavan et al, 2017) at a low cost in natural resource management systems. Bamboo is known as one of the fastest growing species of plants (Zhou et al, 2011). There is also a substantial difference between bamboo forest and other forests. Bamboo has rapid growth and high re-growth rates when properly handled. The living cycle of bamboo culms (around 5-8 years) is comparatively shorter than that of most species of trees. Bamboo is commonly used in lower durability products than those in timber products. However, owing to the recent technological advancements in bamboo processing, bamboo can now be processed into very durable products.

Bamboo has a unique dense rhizome structure that helps in accelerating the growth rate of bamboo shoots and culms. Thanks to special biological characteristics of the rhizome, when a bamboo culm is harvested the bamboo rhizome system is still alive and continues to produce shoots. There are two main types of rhizome: (a) monopodial (running) and (b) sympodial (clumping). Running bamboo has the rhizome that spreads horizontally and forms the dispersed bamboo, whereas clumping bamboo has the shorter rhizome, is formed together and forms the bamboo clumps (Lobovikov et al, 2007; Kaushal et al, 2018). There are two groups of bamboo, consisting of a group of herbaceous bamboo species and the other of woody bamboo species. Carbon is different among these groups of bamboo.

2. The role of bamboo forest for socio-economic development, environment protection and climate change mitigation and adaptation

Bamboo is an important non-timber forest product and is an incredible resource to fight poverty (Ricardo et al, 2013; Sohel et al, 2015). Bamboo forests are useful for the poor in the tropics, where they offer a wide range of products as a means of livelihood. Bamboo forest sustainable management helps stabilise the livelihood of millions of poor people in the rural areas and mountains (Yuen, Fung and Ziegler, 2017). Bamboo is considered a multipurpose plant, consisting of about 10,000 usages (INBAR; bamboo facts), such as medicine, folders, housing, crafts, pulp, paper, panels, boards, veneer, flooring, roofing, fabrics, oil, gas and charcoal; it is also a good vegetable (the bamboo shoot). The bamboo industry is thriving in Asia and rapidly spreading to Africa and the United States (Lobovikov et al, 2007). It is estimated that 2.5 billion people are directly producing and consuming bamboo (Canavan et al, 2017).

Bamboo plays an important role in economic security and employment opportunities for the unemployed (Tariyal, 2016). According to Ly et al (2012), from an economic perspective, bamboo products have become popular both in the developed countries as an attractive material for house decorating and construction and in the developing countries for their potential role in rural development. Bamboo represents a promising opportunity for strengthening the economic security of people with low incomes.

Bamboo is also a very important ecological plant, with extensive rhizome and root networks and a dense canopy which help decrease soil erosion and run-offs and thereby improve the maintenance of the nutrients and regulations of water flow in rivers and lakes (Yuen, Fung and Ziegler, 2017). Bamboo is also a cultural feature of South and Southeast Asia.

In the context of climate change, bamboo provides some ecosystem services, which benefit carbon sequestration. Bamboo can sequester a substantial amount of carbon in its above-ground biomass (AGB), below-ground biomass (BGB) and Soil Organic Carbon (SOC) (Ly et al, 2012). Therefore, bamboo forests are an important resource for mitigating climate change (Ricardo et al, 2013; Sohel et al, 2015; Yuen, Fung and Ziegler, 2017). The sustainable management of bamboo forests that grow rapidly can support the objectives of the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD).

Despite the botanical classification, bamboo is a woody grass; however, it is capable of sequestering carbon when compared to other timber forests. As fast-growing species, organic carbon sequestration, due to photosynthesis, is substantial in culms, branches and leaves as well as in rhizome and root networks of bamboo (Yiping et al, 2010; Ricardo et al, 2013; Yuen, Fung and Ziegler, 2017). The sequestration of carbon in bamboo forests is similar to or larger than that of fast-growing timber plantations (Sohel et al, 2015). Above-ground carbon (AGC) of bamboo forest ranges from 16-128 tonne C ha^{-1}, below-ground carbon (BGC) biomass from 8-64 tonne C ha^{-1}, SOC from 70-200 tonne C ha^{-1} and total ecosystem carbon ranges from 94-392 tonne C ha^{-1} (Yuen, Fung and Ziegler, 2017; Li, Lin and Yen, 2016). Therefore, in terms of carbon cycle, bamboo forests have comparable characteristics to other forest types, such as the tropical rainforests in Asia which contain 56-320 tonne of C ha^{-1} in the AGB pool (IPCC, 2003, 2006). Bamboo forests demonstrate significant carbon sequestration as an efficient and effective carbon sink (Yiping et al, 2010; Yuen, Fung and Ziegler, 2017).

INBAR and partners have set out to determine the way bamboo behaves towards the bamboo carbon cycle in order to integrate bamboo into national climate change mitigation strategies and plans. Given the potential of bamboo forests for sequestering carbon, bamboo deserves to be better recognised in forest policies and management (Yuen, Fung and Ziegler, 2017) and to be included in the measurement, reporting and verification system of the UN-REDD programme.

3. Definitions of four biomass and carbon pools in bamboo forest

The IPCC (2003, 2006) guidance, which is specific to the bamboo forest, consists of four main carbon pools, as shown below:

1.AGB consists of the following:
- o Bamboo AGB
- o Non-bamboo vegetation AGB

2.BGB consists of the following:
- o Bamboo BGB, comprising rhizome and root networks
- o Non-bamboo vegetation BGB

3.Litter

4.SOC

Figure 1 illustrates the four carbon pools in the bamboo forest.

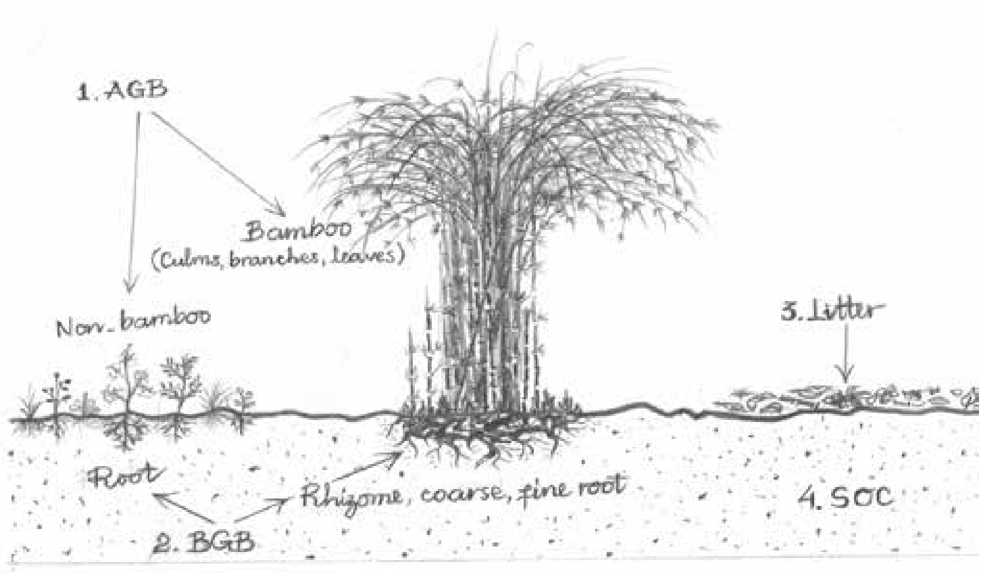


Figure 1. Four carbon pools in the bamboo forest: AGB, BGB, litter biomass (B_{li}) and SOC (Sketch: Nguyen Thi Thao, 2019).

3.1. AGB and AGC in bamboo forests

AGB in bamboo forest is living biomass above the soil (IPCC, 2003; Food and Agriculture Organization [FAO], 2010), which includes

- biomass in bamboo culms, branches and leaves; and

- biomass in non-bamboo vegetation, including herbaceous plants, grasses and shrubs.

In cases where the forest understorey is a relatively small component of the AGB carbon pool, it is acceptable to exclude it, provided this is done consistently throughout the inventory time series.

AGC in the bamboo forest includes carbon in all living biomass above the soil (FAO, 2010).

3.2. BGB and BGC in bamboo forests

BGB in bamboo forests is all biomass of live roots (IPCC, 2003; FAO, 2010), which includes

- biomass in the root system of bamboo, including rhizome, coarse and fine roots larger than 2 mm in diameter and the depth of 60 cm where the bamboo root system can reach (Zhang et al, 2014; Kaushal et al, 2018); and

- biomass in root of non-bamboo vegetation more than 2 mm in diameter.

Different countries may use thresholds other than the value of 2 mm for fine roots; however, in such a case, the threshold values used must be documented. BGC in bamboo forests includes carbon in all biomass of live roots (FAO, 2010).

3.3. Carbon in litter

Carbon in litter is all non-living biomass (dead bamboo leaves, branches, culms, culm sheaths, flowers, fruits, dead components of other vegetation, etc.) with a diameter less than the minimum set diameter (e.g. 10 cm), standing and/or lying dead in various states of decomposition above the mineral or organic soil (IPCC, 2003; FAO, 2010).

Living fine roots of less than 2 mm (or other values chosen by a country as diameter limit for BGB) above the mineral or organic soil are included in the litter, where they cannot be distinguished from it empirically.

3.4. SOC

Organic carbon in mineral and organic soils (including peat) is, to a specified depth, chosen by countries and applied consistently through the time series (IPCC, 2003; FAO, 2010). Live fine roots of less than 2 mm (or other values chosen by a country as the diameter limit for BGB) are included in soil organic matter, where they cannot be distinguished from it empirically.

SOC per unit area is calculated using following equations (Pearson, Brown and Birdsey, 2007; Yuen, Fung and Ziegler, 2017):

$$SOC\ (tonne\ ha^{-1}) = \rho \times d \times \%C \times 100, \quad (1)$$

where ρ is soil bulk density (g cm^{-3}) = dry soil weight of soil core (g)/volume of soil core (cm^3); d is soil depth (cm), chosen by countries (normally 30 or 50 cm); and $\%C$ is the percentage of organic carbon in the dry soil core sample.

4. Time series for measuring and reporting bamboo forest biomass and carbon integrated in the National Forest Inventory

According to the IPCC (2006), each country or territory should establish a time series for measuring and reporting carbon emissions and removals from forests. These data normally contain changes in the forest area (activity data) and the carbon sequestration in the forest pools, usually only measured by an interval of a few years. Hence, it is necessary to periodically identify a suitable forest inventory with a regular forest monitoring system.

Normally, each country or territory has a forest inventory period of 5-10 years, with a system of annual (or longer) data updating. Therefore, measuring and reporting of carbon from bamboo forests is also included in this system. Measuring and monitoring carbon in bamboo forests should comply with the national and regional forest inventory regimes; they should include the same plot layout system and monitoring cycle. However, compared to wood forest, there are also specific characteristics such as sample plot type (plot shape and size), measured parameters for biomass and carbon estimation of pure bamboo forest or mixed wood bamboo forest.

Chapter II. METHODS OF ESTIMATING BIOMASS AND CARBON IN POOLS OF BAMBOO FORESTS: DEVELOPMENT AND CROSS-VALIDATION OF ALLOMETRIC EQUATIONS

1. Overview of methodology to estimate biomass and carbon in pools of bamboo forests

This section presents an overview of the methods of estimating and assessing biomass and carbon in bamboo forests, which focuses on three pools of AGB, BGB and litter (Table 1). In UN-REDD projects, it is usually cost-effective to neglect SOC, methodology permitting (Petrova et al, 2010). In addition, SOC in bamboo forests resembles other forest types completely (see the instructions of Hairiah et al, 2001; Pearson, Brown and Birdsey, 2007 and Subedi et al, 2010); thus, this manual does not instruct on the measurement and assessment of SOC.

Table 1. Overview of methods for measuring and estimating bamboo biomass and carbon in three main pools

Carbon pools in bamboo forests	Method of measurement in the field	Method of developing allometric equations
1. AGB/carbon		
Living bamboo	*Non-destructive measurement:* Use available (or develop) allometric equations to estimate above-ground biomass of bamboo plant (AGB_{bamboo}); measuring predictors mentioned in the selected allometric equations include - Culm-based measurement: measuring D, H and A of a bamboo plant - Clump-based measurement: measuring clump – diameter of bamboo culm (D_{clump}), height of bamboo clump (H_{clump}) and number of culms per clump (N_{culm})	*Destructive measurement:* - Fell culms or clumps to measure biomass of bamboo components and AGB_{bamboo} - Develop and validate bamboo AGB allometric equations: $AGB_{bamboo} = f(D, H, A)$ AGB of biomass clump: Above-ground biomass of bamboo clump $(AGB_{clump}) = f(D_{clump}, H_{clump}, N_{culm})$
Non-bamboo understorey vegetation	*Destructive measurement:* Where non-bamboo vegetation is small (< 30 cm high): measuring biomass by simple harvesting techniques in small subplots	
	Non-destructive measurement: Where non-bamboo vegetation is large (> 30 cm high). Use available (or develop) allometric equations to estimate non- bamboo AGB ($AGB_{non-bamboo}$); measuring predictors mentioned in the selected allometric equation, such as crown diameter (CD), height (H) and/or diameter at base (D_0) of plant in subplots	*Destructive measurement:* - Harvest non-bamboo vegetation to measure biomass - Develop and validate the $AGB_{non-bamboo}$ allometric equations: $AGB_{non-bamboo} = f(CA, H, D_0)$

Carbon pools in bamboo forests	Method of measurement in the field	Method of developing allometric equations
2. BGB/carbon		
Bamboo root: rhizome, coarse and fine roots	*Non-destructive measurement*: Use Root-Shoot Ratio (RSR), if available. No measurement	
	Non-destructive measurement: Use available (or develop) allometric equations to estimate BGB_{bamboo}; measuring predictors mentioned in the selected allometric equations include - Culm-based measurement: measuring D, H and A - Clump-based measurement: measuring D_{clump}, H_{clump} and N_{culm}	*Destructive measurement*: - Quadrat excavation of rhizome, coarse and fine roots to measure the biomass of bamboo root components and BGB - Develop and validate bamboo BGB allometric equations: $BGB_{bamboo} = f(D, H, A)$ $BGB_{clump} = f(D_{clump}, H_{clump}, N_{culm})$
Non-bamboo vegetation root	*Destructive measurement*: Use soil core to measure the biomass of non-bamboo vegetation root	
3. Dead mass and carbon in litter	*Destructive measurement:* Use a small frame and litter within the frame collected and weighed	
	Non-destructive measurement: Where the litter layer is well defined and deeper than 5 cm, use available (or develop) equations that relate the depth of the litter to the mass per unit area; measuring predictors mentioned in the selected allometric equations, such as litter depth (LD) in frames; standing dead culm-based measurement: measuring D of standing dead bamboo culm simultaneously along with living bamboo plants measurement in sample plots with remark 'dead culm'	*Destructive measurement*: - Sample the litter in the frames along with the full range of the expected LD - Develop and validate litter biomass (B_{li}) allometric equations: $B_{li} = f(LD)$ - Fell standing dead bamboo culms to measure dead mass and develop, validate standing dead bamboo culm mass ($Bdead_{cu}$) allometric equations: $Bdead_{cu} = f(D, H)$. Method for developing equation for standing dead bamboo culms mass is the same as living bamboo plant biomass mentioned above.

In terms of field measurement for biomass carbon estimates, to reduce costs and impact on the forest, we should primarily adopt the non-destructive method. This method collects data according to the variables and predictors of appropriate allometric equations, which have been developed to estimate forest, plant biomass and carbon. Meanwhile, the destructive method is applied to collect the data set for modelling equations to estimate the biomass and carbon in AGB_{bamboo}, $AGB_{non-bamboo}$, AGB_{clump}, BGB_{bamboo} (rhizome, coarse and fine roots), BGB_{clump} and B_{li}; these models have long-term use in local and/or ecological regions, depending on the scale of location where the data set is collected. However, this method destroys the forest within sample plots and requires funds and resources; therefore, it must be limited to developing and validating the models; in the long run, the developed models should then be applied to large areas and regions. This method cannot be adapted to frequent field inventories and measurements.

At the moment, we are unable to develop (or have not yet established) allometric equations for estimating biomass and carbon in non-bamboo understorey vegetation and non-bamboo vegetation root and litter; the destructive method can be used to estimate those biomass and carbon in bamboo forests.

2. The growing forms of bamboos vs different measurement methods

The bamboo plant is either clump forming (clumping bamboos) or non-clump forming (running bamboos). A clump is a cluster of bamboo culms (Kaushal et al, 2018) (Figure 2).

Gigantochloa sp.
Photo: Bao Huy, 2018
Clumping bamboo

Bambusa sp.
Photo: Bao Huy, 2016
Running bamboos

Figure 2. The growing forms of bamboo.

All bamboos spread via their rhizomes. Whereas running bamboos (monopodial) have long rhizomes, which spread horizontally, clumping bamboos (sympodial) have shorter rhizomes, which bring bamboos together (Figure 3).

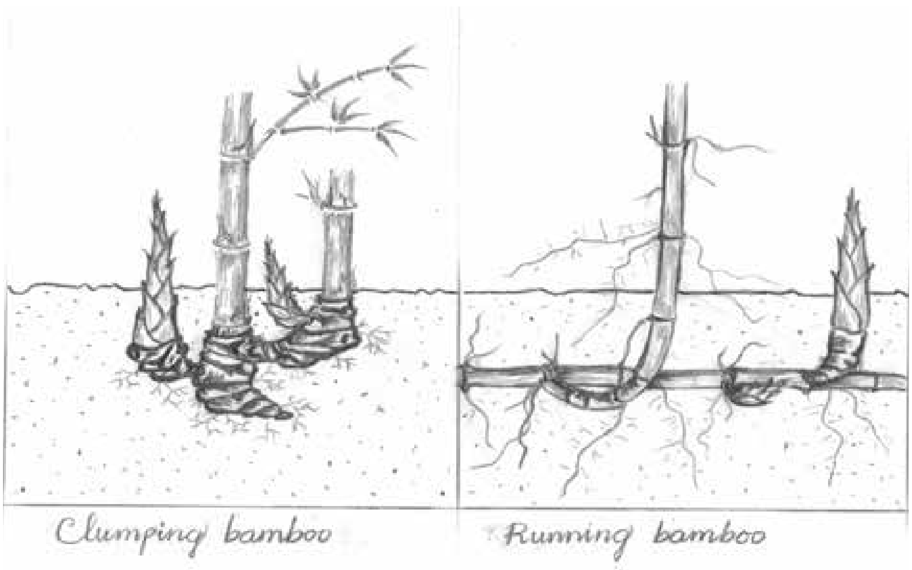


Figure 3. Two main forms of rhizomes of bamboo (Sketches: Nguyen Thi Thao, 2019).

Given the different growing forms of bamboo, the bamboo measurement can be divided into two main categories:

- Culm-based measurement, which is for running bamboo or clumping bamboo with long necked rhizomes (sparse culms). In the field, it is possible to measure all individual culms in the sample plot or each culm in clump with sparse culms.

- Clump-based measurement, which is for clumping bamboo with very dense culms (short necked rhizomes). The measurement of each culm in clump is impractical. Therefore, variables of bamboo clump and/or representative culms can be measured.

3. Methods of estimating biomass and carbon in AGB pool

3.1. For AGB_{bamboo}: non-destructive measurement

To apply the non-destructive method to collect data in the field, AGB models are used to estimate carbon biomass; these models are set based on destructive data. The next chapter of this section introduces the method of destructive bamboo, sampled to develop the allometric equations for bamboo biomass and carbon estimates.The data collection is divided into two groups:

- Culm-based measurement in sample plots, which is for running bamboo or clumping bamboo with no dense culms. In a sample plot system, the collected data are the predictors of the model, used to estimate bamboo plant AGB. Normally, the variables that need to be measured are D (cm), H (m) and A (year) of bamboo culms, in which the H predictor only needs to be measured in a similar fashion to all culms because most bamboo culms reach the elongation and then maximal height in the first year (Kaushal et al, 2018).

- Clump-based measurement, which is for clumping bamboo with very dense culms:
    - o Measuring predictors of selected plant AGB_{bamboo} models such as D and H of averaged culms per A groups and the counting number of culms per A in the sample plot system; in this case, the allometric equations for AGB_{bamboo} are used.
    - o Measuring predictors of the selected AGB_{clump} models, such as clump girth (G_{clump}), D_{clump}, H_{clump}, N_{culm} and the number of clumps per unit area (N_{clump}) (Kumar, Rajesh and Sudheesh, 2005). In this case, the allometric equations for AGB_{clump} are used. However, this model of estimating AGB_{clump} is rare because of the difficulty collecting destructively bamboo clump biomass to develop and validate the allometric equations for AGB_{clump}. Therefore, this method should be restricted.

3.2. For $AGB_{non\text{-}bamboo}$

Non-bamboo vegetation (except the tree in this manual) such as herbaceous plants, grasses and shrubs can occur as components of a forestry project (IPCC, 2003). With $AGB_{non\text{-}bamboo}$, it is possible to choose either a destructive or non-destructive method in the following ways. In case there are trees in the sample plot, normally identify the species and its wood density and measure predictor(s) such as D and H for the estimation of carbon in trees (see another manual, such as Pearson, Brown and Birdsey, 2007; Subedi et al, 2010; Petrova et al, 2010; Huy, Sharma and Quang, 2013).

3.2.1. Destructive method for $AGB_{non\text{-}bamboo}$ measurement

When shrubs are small (< 30 cm high) (Petrova et al, 2010), herbaceous plants in the forest understorey can be measured using simple harvesting techniques of up to four small subplots per permanent or temporary plot (IPCC, 2003). These subplots can be circular or rectangular and can be made from various materials. There are different sizes of subplots, made using a PVC pipe, such as 0.25 m^2 (50 cm x 50 cm) (Pearson, Brown and Birdsey, 2007; Petrova et al, 2010), 0.5 m^2 (70.7 cm x 70.7 cm) (Dung, Anh and Vinh, 2018; IPCC, 2003), 1 m^2 (1 m x 1 m) (Hairiah et al, 2001) and a 3.14 m^2 circular subplot (R = 1 m) (Subedi et al, 2010). The selection of the appropriate subplot size depends on the non-bamboo vegetation density. For bamboo forests, vegetation in forest understorey is not too dense;

hence, a subplot size of 0.5 m^2, according to the IPCC guidance (2003), is appropriate.

All non-bamboo plants in all subplots are harvested, and fresh biomass of non-bamboo vegetation is weighed in the field. Well-mixed sub-samples from each subplot are then oven-dried to determine the dry-to-fresh biomass ratios in laboratory. These ratios are then used to convert the entire fresh biomass of non-bamboo vegetation in all subplots to oven-dry biomass ($AGB_{non\text{-}bamboo}$) (IPCC, 2003; Petrova et al, 2010).

3.2.2. Non-destructive for $AGB_{non\text{-}bamboo}$ measurement

An alternative approach is that, if the shrubs are large (> 30 cm high), the non-destructive method may apply if the model for $AGB_{non\text{-}bamboo}$ already exists (Petrova et al, 2010). The data collected include the predictors of the biomass model of $AGB_{non\text{-}bamboo}$. The same subplot is also used as the destructive method mentioned above (e.g. four subplots of 0.5 m^2). Proceed to measure the predictors of each shrub in the subplot, which may be the CD and/or H and/or D_0. Then use the model to estimate biomass and carbon for $AGB_{non\text{-}bamboo}$ in unit areas.

Where no allometric equation already exists, it will be necessary to apply the destructive method to collect biomass data and develop a new equation for estimating the $AGB_{non\text{-}bamboo}$ (Petrova et al, 2010; Pearson, Brown and Birdsey, 2007). The model for estimating $AGB_{non\text{-}bamboo}$ should have predictors of crown area (CA), H or D_0 or another relevant variable (Pearson, Brown and Birdsey, 2007). The next chapter of this section introduces the method of destructive non-bamboo, sampled to develop the allometric equations for estimating biomass and carbon of $AGB_{non\text{-}bamboo}$.Conditions and recommendations for selecting appropriate methods

The following options are available for choosing the appropriate method of measuring $AGB_{non\text{-}bamboo}$:

- If $AGB_{non\text{-}bamboo}$ is negligible, it is acceptable to exclude it, provided this is done consistently throughout the inventory time series.

- Typically, the destructive method is used to estimate $AGB_{non\text{-}bamboo}$. However, this method needs to collect a large amount of biomass samples, which brings to the laboratory to determine the fresh-to-dry biomass ratios; therefore, this is generally expensive and requires more resources. Thus, the decision as to whether $AGB_{non\text{-}bamboo}$ should be measured or not needs to be taken, and it should be based on available resources and the significant amount of the carbon pool in the bamboo forests at the surveyed area.

- The non-destructive method is applied well when models of the $AGB_{non\text{-}bamboo}$ estimates are available. However, these models are often limited, whereas modelling for $AGB_{non\text{-}bamboo}$ is not difficult but requires funds and resources.

4. Methods of estimating biomass and carbon in BGB pool

4.1. For BGB_{bamboo}: non-destructive measurement

Basically, the direct measurement of BGB_{bamboo} is difficult, mainly because of the complex rhizome and root system of bamboo. Therefore, surveys and inventories mainly apply the non-destructive measurement to collect data on predictors of the models which are available for estimating BGB_{bamboo}. Meanwhile, to set up the BGB_{bamboo} models, the destructive measurement needs to be applied to collect the data set of the predictors and responses. Modelling is set once for a local and/or regional/ecological area and is then applied in the long run. The next chapter of this section introduces the method of destructive bamboo plant sampled to develop the allometric equations for estimating biomass and carbon of BGB_{bamboo}.

4.1.1. Non-destructive measurement, using the available Root-Shoot Ratio (RSR)

Some research results have thus far reported on RSR, which include the ratios of BGB to AGB (Table 2). RSR is determined according to each species in each locality, territory or country. The RSR values indicated in Table 2 can be used to estimate the value of BGB_{bamboo} from the value of AGB_{bamboo}. In this case, the inventories and surveys will not be necessary to measure any variables in the field.

Table 2. The available RSR of BGB to AGB

ID	Bamboo species	Author(s) (year)	Location, region	RSR
1.	*Dendrocalamus membranaceus*	Yuen, Fung and Ziegler (2017) collected	China	0.12
2.	*Dendrocalamus strictus*	Idem	India, Myanmar	0.86
3.	*Fargesia denudate*	Idem	China	0.90
4.	*Gelidocalamus stellatus*	Idem	China	0.76
5.	*Gigantochloa apus*	Idem	Indonesia	0.13
6.	*Gigantochloa spp.*	Idem	Indonesia, Thailand	0.72
7.	*Guada angustifolia*	Idem	Bolivia, Colombia, Ecuador	0.15
8.	*Neosinocalamus affinis*	Idem	China	0.21
9.	*Oligostachyum oedognatum*	Idem	China	0.89
10.	*Phyllostachys atroviginata*	Idem	China	1.65
11.	*Phyllostachys bambusoides*	Idem	Japan, South Korea	0.44

ID	Bamboo species	Author(s) (year)	Location, region	RSR
12.	*Phyllostachys edulis*	Kuehl, Lia and Henley (2013)	China	0.31-0.36
13.	*Phyllostachys edulis*	Wang et al (2013)	China	0.41-0.49
14.	*Phyllostachys edulis*	Yuen, Fung and Ziegler (2017) collected	China, Japan, Korea, Taiwan	0.55
15.	*Phyllostachys heteroclada*	Idem	China	1.97
16.	*Phyllostachys makinoi*	Idem	Taiwan	2.79
17.	*Phyllostachys meyeri*	Idem	China	1.40
18.	*Phyllostachys nidularia*	Idem	China	0.56
19.	*Phyllostachys nigra*	Idem	South Korea	0.53
20.	*Phyllostachys praecox*	Idem	China	0.42
21.	*Phyllostachys rutila*	Idem	China	1.72
22.	*Phyllostachys viridis*	Idem	China	2.60
23.	*Pleioblastus amarus*	Idem	China	0.65
24.	*Pseudosasa amabilis*	Idem	China	0.78
25.	*Pseudosasa usawai*	Idem	Taiwan	1.13
26.	*Qiongzhuea tumidinoda*	Idem	China	0.82
27.	*Sasa kurilensis*	Idem	Japan	0.39
28.	*Sasa nikkoensis*	Idem	Japan	0.69
29.	*Sasa nipponica*	Idem	Japan	0.91
30.	*Sasa oseana*	Idem	Japan	0.69
31.	*Sasa senanensia*	Idem	Japan	1.06
32.	*Schizostachyum lumampao*	Idem	Philippines	0.30

4.1.2. Non-destructive measurement, using available allometric equations

To apply the non-destructive method to collect data in the field, the BGB_{bamboo} models are used to estimate carbon biomass; these models are developed according to destructive data. The next chapter of this section details the method of destructive bamboo root system including rhizome, coarse and fine to develop allometric equations for BGB_{bamboo} estimate. In fact, if this method is applied, the investigation does not require any additional variables to be measured; the predictors measured to estimate the AGB_{bamboo} mentioned above can also be used to estimate the BGB_{bamboo}. The predictors are as follows: D, H, A, N_{culm}, G_{clump}, D_{clump}, H_{clump} and N_{clump}.

Very few models have thus far been used to estimate BGB_{bamboo}, mainly because of the difficulty in gathering data sets to develop the equations. To date, no equations for estimating the BGB components of bamboo have been found in Southeast Asia (Yuen, Fung and Ziegler, 2017).

4.1.3. Conditions and recommendations for selecting appropriate methods

The investigation of estimating BGB_{bamboo} is mainly applied to non-destructive methods. Where there is no BGB_{bamboo} model, the easiest way is to apply RSR to estimate BGB_{bamboo} from AGB_{bamboo}. When the model for BGB_{bamboo} exists, there is no need to measure any variable in the field; the predictors measured for AGB_{bamboo} estimates can also be used for estimating BGB_{bamboo} through the selected models. When there is neither RSR nor a model for BGB_{bamboo} estimates, the following two options are recommended: (a) ignoring BGB_{bamboo} pool measurement, which should be done consistently throughout the inventory time series; and (b) developing the BGB_{bamboo} model for local and/or ecological regions using the method of destructive data set, which is introduced in the next part of this section.

4.2. For $BGB_{non-bamboo}$: destructive measurement

The soil core method has been found to be a quick method for evaluating root distributions in the forest (IPCC, 2003). Various soil core sizes are used, with a diameter ranging from 4-10 cm and a length of 6-30 cm (Lackmann, 2011). Soil core is used to take a soil sample which includes the non-bamboo root biomass. Soil samples are taken according to one of these three soil layers: 0-30 cm, 30-50 cm or > 50 cm. The fresh non-bamboo roots are obtained from the soil core, weighed in the field and converted to the unit area (e.g. ha). The destructive non-bamboo root samples are brought to the laboratory to determine the fresh-to-dry ratios and to calculate the dry-root biomass of the $BGB_{non-bamboo}$.

5. Methods of estimating biomass and carbon in litter pool

5.1. Destructive measurement

Litter can be directly sampled using a small frame (either circular or square) (IPCC, 2003). The subplots are the same as those used to measure the $AGB_{non\text{-}bamboo}$ mentioned above. For bamboo forests, a subplot size of 0.5 m^2, according to the IPCC guidance (2003), is appropriate. According to its definition, all litter in all subplots is collected, and the fresh biomass of litter is weighed in the field. Well-mixed sub-samples from each subplot are then brought to the laboratory to determine the dry-to-fresh biomass ratios. Those ratios are then used to convert the entire fresh B_{li} in all subplots to oven-dry biomass.

5.2. Non-destructive measurement

An alternative approach where the litter layer is well defined and deep (more than 5 cm in depth) is to develop or use a local/regional regression, which relates the depth of the litter to the mass per unit area (IPCC, 2003). The next chapter of this sentence presents the destructive method of collecting data sets for developing the model for estimating B_{li}.. In the field, the non-destructive method is applied, measuring the predictor(s) mentioned in the selected allometric equations (e.g. LD) in frames (subplots), and using the appropriate allometric equation to estimate B_{li}.

5.3. Conditions and recommendations for selecting appropriate methods

A destructive measurement requires many samples of litter mass from subplots, which are brought to the laboratory to determine the dry-to-fresh ratios; these samples are repeatedly taken from each forest inventory; thus, this method is extremely costly. If the litter mass is thin and negligible (e.g. in rainforests), it is possible to ignore this carbon pool for cost-effectiveness.

A non-destructive measurement applies to the field measurement; however, this method needs available equations for estimating B_{li} in the bamboo forest in a suitable ecoregion. The collection of data sets for modelling is not difficult. Therefore, instead of considerable litter with a thickness of over 5 cm – and this carbon pool is substantial – the model to estimate biomass should involve carbon of litter, developed for long-term use (IPCC, 2003).

6. Development and validation of allometric equations for estimating biomass and carbon in bamboo forests

6.1. The need to develop allometric equations for estimating biomass and carbon of bamboo

The model for the assessment of biomass carbon in the forest has been established for different forest types in different site conditions; however, it focuses mainly on species of large trees (Brown, 1997; Chave et al, 2005; Basuki et al, 2009; Chave et al, 2014; Huy et al, 2016a, 2016b, 2019a,b; Huy, Poudel and Temesgen, 2016). Although a bamboo forest is a unique forest type with a significant carbon storage capacity, there are few biomass and carbon equations (Isagi, Kawahara and Ito, 1997). The existing IPCC guidelines (IPCC 2003, 2006) ignore bamboo forests, and there is no guidance on biomass carbon assessment and emission reports.

Most of the bamboo biomass models have been developed in China, Taiwan, Japan and India, predominantly for *Phyllostachys edulis* and *Dendrocalamus latiflorus* species (Yuen, Fung and Ziegler, 2017). GlobAllomeTree database, a global biomass database, contains biomass allometric equations for six bamboo species (*Bambusa balcooa, Bambusa bambos, Bambusa cacharensis, Bambusa procera, Bambusa vulgaris* and *Indosasa angustata*) (Henry et al, 2013). Meanwhile, the number of bamboo species is incredibly large; there are over 1600 bamboo species globally, consisting of 75-107 genera worldwide that are widely distributed across tropical and subtropical regions. In order to gain reliable bamboo biomass estimates, the models of AGB and BGB should be species-specific and ecoregion-specific equations. This requirement illustrates that there is a considerable need to develop a full range of bamboo carbon estimation models globally.

6.2. Data collection and measurement of variables for different allometric equations

6.2.1. Sample plot

A sample plot needs to be applied to collect information on forest structure to select suitable sample bamboo plants. In addition, to assess the random effects of the environmental ecological factors on biomass estimation models, different ecological and site factors at the sample plot locations need to be collected; each site of least 3-5 plots should be set up. The size and shape of the sample plots must be consistent across the sample plot system. The size of the plots depends on the density of the bamboo; the minimum area of the plot should ensure 30-50 culms. The normal size is from 100 m^2 (bamboo density over 10,000 culms ha^{-1}) to 500 m^2 (bamboo density under 1000 culms ha^{-1}) with a square or circular shape.

At the plot, it is necessary to collect information about the site, including ecological factors such as average rainfall, average temperature, soil type, soil colour, soil thickness, slope and altitude. Within the plot, D (cm) and H (m) should be recorded (since bamboo culms reach their full height in the first year; afterwards, there is no change in height [Tran, 2010; Kaushal et al, 2018]; thus, it is only necessary to measure average H of the bamboo clump). Bamboo age (A, year) is identified directly from its morphological features (Huy, Sharma and Quang, 2013; Li, Lin and Yen, 2016). Use Table 3 to record the information and data collected at the sample plot.

Table 3. Sample plot information and data for bamboo allometric equation development

Plot information

Plot ID:	Coordinate: X: Y:
Plot size: Plot shape:	Species of bamboo: Forest type:
Average culm height (m):	G_{clump} (cm) (if applicable):
Average rainfall (mm $year^{-1}$):	Average temperature (^0C $year^{-1}$):
Soil type: Soil colour:	Soil thickness (cm):
Slope (degree):	Altitude (m):
Recorded by:	Date:

Data of culm

Culm ID	Culm age (A, year)	Culm diameter at breast height (D, cm)	Culm ID	Culm age (year)	Culm diameter (D, cm)

Note: *Record all variables with one decimal place except A.*

6.2.2. Destructive sample for developing plant AGB_{bamboo} model

The destructive bamboo samples are selected at the sample plots; these samples need to be collected within the full range of D and A classes. The number of culm samples per plot is about 10 culms, each of age 1-5 select 2-3 culms, with 3-5 plots for each site. There are approximately 30–50 sample culms, considering the modelling for a locality and a specific site. If the model on multiple sites is developed, each site repeats at least 30-50 sample culms. The number of destructive sample culms should be distributed in the same proportion to the distribution of the diameter of the bamboo forest. Figure 4 shows that the diameter distribution of destructively sampled bamboo culms is the same as the diameter distribution of the bamboo forests.

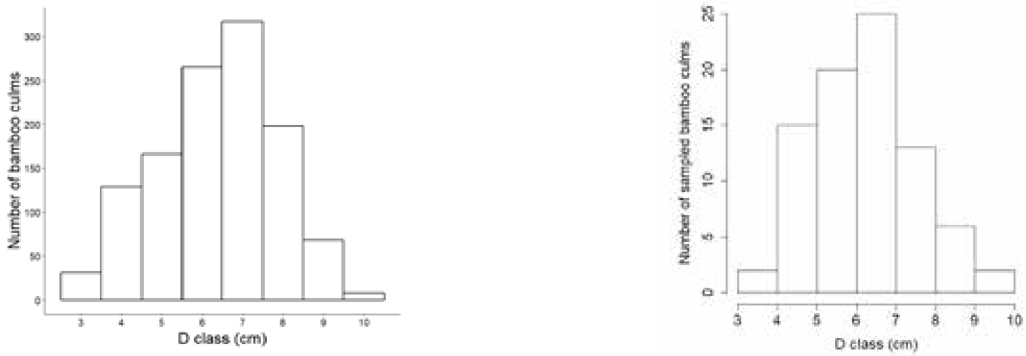


Figure 4. D istribution of bamboo culm diameter (D, cm) of sample plots; distribution of bamboo culm diameter (D, cm) of required destructively sampled bamboo culms (left to right, respectively).

After cutting, sampled bamboo culms are re-measured for length. The fresh biomass of three components of bamboo (e.g. culms, branches and leaves) is separated and weighed on site (Figures 5 and 6).

Figure 5. Leaves, branches and culms of the destructively bamboo sample are separated on site (Photo: Bao Huy, 2019).

Figure 6. Fresh biomass of leaves, branches and culms are weighed on site (Photos: Bao Huy, 2019).

Samples for each bamboo component (e.g. culms, branches and leaves) are taken and brought to the laboratory to determine the fresh-to-dry mass ratios. A sample of approximately 100-300 g is obtained for each component: culms (at three positions on the culm: root collar, middle and top), branches and leaves, including young and old ones. As the water in the fresh sample will evaporate during the investigation and transport to the laboratory causing a change in the fresh mass of the sample, the fresh mass of samples should be weighed on site using a precision electronic scale to 0.1 g'. (Figure 7). Use the form in Table 4 to record the data on the destructively sampled bamboos.

Figure 7. Samples of leaves, branches and culms are weighed using a precision electronic scale on site and brought to the laboratory to determine the fresh-to-dry mass ratios (Photos: Bao Huy, 2019).

Table 4. Data set of destructively sampled AGB_{bamboo} plant

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Bamboo plant sample ID	D (cm)	H (m)	A (year)	Fresh biomass of culm (kg)	Fresh biomass of branches (kg)	Fresh biomass of leaves (kg)	Fresh mass of culm samples (g)	Fresh mass of branch samples (g)	Fresh mass of leaf samples (g)

Note: *Record all variables with one decimal place except A.*

6.2.3. Destructive sample for developing AGB_{clump} model

In case of clumping bamboo with very dense culms, it is difficult to reach to measure each bamboo plant in a dense clump. Modelling AGB_{clump} can be conducted to estimate the bamboo biomass of a clump by using predictors of clump-based measurement, such as D_{clump}, H_{clump} and N_{culm}. For example, Kumar, Rajesh and Sudheesh (2005) developed models to estimate AGB_{clump}, where the predictor is D_{clump}. Clumps are destructively sampled. Before felling the bamboos, G_{clump}, H_{clump} and N_{culm} need to be measured. The number of clumps for destructively sampled clumps should be 30-40 clumps per site and represent a range of D_{clump} sizes ($D_{clump} = G_{culm/\pi}$). Afterwards, cutting will continue by separating the leaves and branch culms and weighing their fresh biomass in the field.

Samples for each bamboo component (e.g. culms, branches and leaves) are brought to the laboratory to determine the fresh-to-dry mass ratios. Approximately 100-300 g sample is for each component: culms (at ages of 1, 3 and 5), branches and leaves, including young and old ones. The fresh weights of samples should be weighed on site using a precision electronic scale to 0.1 g(Figure 7). Use the form in Table 5 to record the data on the destructively sampled bamboo clumps.

Table 5. Data set of destructively sampled AGB_{clump}

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Bamboo clump sample ID	Gclump (m)	Hclump (m)	Nculm	Fresh biomass of total culms (kg)	Fresh biomass of total branches (kg)	Fresh biomass of total leaves (kg)	Fresh mass of culm samples (g)	Fresh mass of branch samples (g)	Fresh mass of leaf samples (g)

Note: *Record all variables with one decimal place except* $N_{culm.}$

6.2.4. Destructive sample for developing shrub biomass model ($AGB_{non\text{-}bamboo}$)

To model the $AGB_{non\text{-}bamboo}$ estimates, it is necessary to collect the biomass of shrub using the destructive method. Approximately 30-50 shrubs per site are cut. The selected shrubs represent a full range of shrub sizes. Before cutting down the plants, it is necessary to identify the species, if applicable, to be able to measure the variables of the shrubs, such as CD of the north to south and east to west, H, D_o (using an electronic caliper to 0.1 mm) (Figure 8). Cut to the ground and weigh the fresh biomass of the plant. Take samples of about 100-300 g per plant, representing all the plant components. The fresh mass of samples should be weighed on site using a precision electronic scale to 0.1 g (Figure 9). Bring samples to the laboratory to determine the fresh-to-dry mass ratios. Use Table 6 to record the data on the destructive non-bamboo samples.



Figure 8. Measuring the shrubs, including predictors of CD, H and D_0 (left to right, respectively) (Photos: Bao Huy, 2019).

Figure 9. Weighing fresh shrub biomass and taking samples, weighed exactly using the precision electronic scale to 0.1 g (left to right, respectively) (Photos: Bao Huy, 2019).

Table 6. Data set of destructively sampled $AGB_{non\text{-}bamboo}$ shrubs

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Shrubs sample ID	Species (if applicable)	CD (cm)		H (cm)	D_0 (mm)	Fresh biomass of plants (g)	Fresh mass of plant samples (g)
		North to south	East to west				

Note: *Record all variables with one decimal place.*

6.2.5. Destructive sample for developing plant BGB_{bamboo} model

The selection of bamboo plant samples to collect data for developing the BGB_{bamboo} plant is conducted at the same time as the destructive samples for the AGB_{bamboo} model. Assuming that the rhizomes, coarse and fine roots of BGB_{bamboo} are evenly distributed underground, the quadrat area is the plot area divided by the total number of culms in the plot. For example, if the plot area is 100 m^2 and the total number of culms of the plot is 50, then the quadrat area = 100 m^2/50 culms = 2 m^2/culm. The quadrat area is in the shape of a circle or square area around the sample bamboo plant (e.g. quadrat area = 2 m^2 as circular area with r = 0.8 m or square area with l = 1.4 m) and then excavated to the depth of 60 cm where the rhizomes and bamboo roots can reach to collect BGB_{bamboo}, consisting of rhizomes and coarse and fine roots (Zhang et al, 2014; Kaushal et al, 2018) (Figure 10).

The fresh BGB_{bamboo} plant components are weighed and recorded separately in the field. Samples for each BGB_{bamboo} component (e.g. rhizomes and coarse and fine roots) are taken and brought to the laboratory to determine the fresh-to-dry mass ratios. Approximately 100-300 g sample for each component is collected. The fresh mass of samples should be weighed on site using a precision electronic scale to 0.1 g (Figure 11). Use the form in Table 7 to record the data of the destructively sampled BGB_{bamboo}.

Figure 10. Excavation of quadrat area of bamboo plant; rhizomes and coarse and fine roots of the destructively sampled bamboo are separated for weighing on site (left to right, respectively) (Photos: Bao Huy, 2019).

Figure 11. Samples of rhizomes and coarse and fine roots (left to right, respectively) are weighed using a precision electronic scale on site and brought to the laboratory to determine the fresh-to-dry mass ratios (Photos: Bao Huy, 2019).

Table 7. Data set of destructively sampled BGB_{bamboo}

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Bamboo plant sample ID	D (cm)	H (m)	A (year)	Fresh biomass of rhizomes (kg)	Fresh biomass of coarse roots (kg)	Fresh biomass of fine roots (kg)	Fresh mass of rhizome samples (g)	Fresh mass of coarse root samples (g)	Fresh mass of fine root samples (g)

Note: *Record all variables with one decimal place except A; ID and D, H and A predictors are the same as Table 4.*

6.2.6. Destructive sample for developing BGB_{clump} model

This method is applicable to clumping bamboo with very dense culms. The selection of bamboo clump samples to collect data for developing BGB_{clump} is conducted at the same time as the destructive samples for the AGB_{clump} model. The entire root system of clump bamboo is excavated to collect the root biomass. The fresh BGB_{clump}, including rhizomes and coarse and fine roots are separated, weighed and recorded in the field. Samples for each component (e.g. rhizomes and coarse and fine roots) are taken and brought to the laboratory to determine the fresh-to-dry mass ratios. Approximately, 100-300 g sample is for each component. The fresh mass of samples should be weighed on site using a precision electronic scale to 0.1 g. Use the form in Table 8 to record the data on the destructive BGB_{clump} samples.

Table 8. Data set of destructively sampled BGB_{clump}

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Bamboo clump sample ID	G_{clump} (m)	H_{clump} (m)	N_{culm}	Fresh biomass of total rhizomes (kg)	Fresh biomass of total coarse roots (kg)	Fresh biomass of total fine roots (kg)	Fresh mass of rhizome samples (g)	Fresh mass of coarse root samples (g)	Fresh mass of fine root samples (g)

Note: *Record all variables with one decimal place; ID and G_{clump}, H_{clump} and N_{culm} predictors are the same as Table 5.*

6.2.7. Destructive sample for developing B_{li} model

Sampling the litter is carried out in the frames of 0.5 m^2 (IPCC, 2003) along with the full range of the expected LDs of the litter on site. The number of frames is approximately 30-50 for each bamboo site. In each frame, measure the LD (mm) to 1 mm, using the electric caliper, and weigh and record the fresh litter mass on site. Take samples of approximately 100 g of litter at each frame and transfer them to the laboratory to determine the fresh-to-dry mass ratios. The fresh mass of samples should be weighed on site using a precision electronic scale to 0.1 g (Figure 12). Use the form in Table 9 to record the data of the destructively sampled bamboo.

Figure 12. Collecting litter mass in frame, weighing litter mass from each frame on site and weighing sampled litter, using a precision electric scale on site left to right, respectively (Photos: Bao Huy, 2019)

Table 9. Data set of destructively sampled litter mass

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Litter subplot sample ID	Fresh B_{li} (g)	LD (mm)	Fresh mass of litter sample (g)

Note: *Record all variables with one decimal place.*

6.2.8. Laboratory work and calculation of predictors and responses for the models

In the laboratory, the samples are split and oven-dried at 105°C (Figure 13) until constant weight to obtain the fresh-to-dry mass ratios of each sample and to calculate the dry biomass (Yen, Ji and Lee, 2010; Huy et al, 2016a).

Figure 13. Dryer machine at 105°C and splitting samples to be oven-dried (left to right, respectively) (Photos: Bao Huy, 2019).

The predictors and responses for different models are as follows:

- AGB_{bamboo}: Dry plant biomass of the culm (B_{cu}, kg), branches (B_{br}, kg), leaves (B_{le}, kg) and AGB_{bamboo} (kg) = $B_{cu} + B_{br} + B_{le}$ (Table 10).

Table 10. Data set for developing plant AGB_{bamboo} models

Recorded by: Date:

Plot ID	Plant ID	D (cm)	H (m)	A (year)	Fresh biomass of culm (kg)	Fresh biomass of branch (kg)	Fresh biomass of leaf (kg)	Ratio culm	Ratio branch	Ratio leaf	Bcu (kg)	Bbr (kg)	Ble (kg)	AGB_{bamboo} (kg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Note: *Columns 1-8 are taken from Table 4; Columns 9-11 are taken from the laboratory; Column 12 = Column 6 × Column 9; Column 13 = Column 7 × Column 10; Column 14 = Column 8 × Column 11; Column 15 = Sum of Columns 12-14. Record all variables with one decimal place except A. Ratios with three decimals.*

- AGB_{clump}: Dry clump biomass of the culm ($B_{cu\text{-}clump}$, kg), branches ($B_{br\text{-}clump}$, kg), leaves ($B_{le\text{-}clump}$, kg) and AGB_{clump} (kg) = $B_{cu\text{-}clump} + B_{br\text{-}clump} + B_{le\text{-}clump}$ (Table 11).

Table 11. Data set for developing AGB_{clump} models

Recorded by: Date:

Bamboo clump sample ID	D_{clump} (m)	H_{clump} (m)	N_{culm}	Fresh biomass of total culms (kg)	Fresh biomass of total branches (kg)	Fresh biomass of total leaves (kg)	Ratio of culm	Ratio of branch	Ratio of leaf	Bcu_{clump} (kg)	Bbr_{clump} (kg)	Ble_{clump} (kg)	AGB_{clump} (kg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14

Note: *Columns 1-7 are taken from Table 5; Columns 8-10 are taken from the laboratory; Column 11 = Column 5 × Column 8; Column 12 = Column 6 × Column 9; Column 13 = Column 7 × Column 10; Column 14 = Sum of Columns 11-13. Record all variables with one decimal place except N_{culm}. Ratios with three decimals.*

- $AGB_{non\text{-}bamboo}$ is presented in Table 12.

Table 12. Data set for developing $AGB_{non\text{-}bamboo}$ models

Recorded by: Date:

Shrub sample ID	Species (if applicable)	Average CD (cm)	CA (cm^2)	H (cm)	D_0 (mm)	Fresh biomass of plant (kg)	Fresh-to-dry ratio mass	$AGB_{non\text{-}bamboo}$ (kg)
1	2	3	4	5	6	7	8	9

Note: *Columns 1-7 are taken from Table 6; Column 8 is taken from laboratory; Column 9 = Column 7 × Column 8. Record all variables with one decimal place except A.*

- BGB_{bamboo}: Dry plant biomass of the rhizomes (B_{rh}, kg), coarse roots (B_{co}, kg) and fine roots (B_{fi}, kg) and BGB (kg) = $B_{rh} + B_{co} + B_{fi}$ (Table 13).

Table 13. Data set for developing plant BGB_{bamboo} models

Recorded by: Date:

Plot ID	Bamboo plant sample ID	D (cm)	H (m)	A (year)	Fresh biomass of rhizomes (kg)	Fresh biomass of coarse roots (kg)	Fresh biomass of fine roots (kg)	Ratio of rhizome	Ratio of coarse root	Ratio of fine root	Brh (kg)	Bco (kg)	Bfi (kg)	BGB_{bamboo} (kg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Note: *Columns 1-8 are taken from Table 7; Columns 9-11 are taken from laboratory; Column 12 = Column 6 × Column 9; Column 13 = Column 7 × Column 10; Column 14 = Column 8 × Column 11; Column 15 = Sum of Columns 12-14. Record all variables with one decimal place except A. Ratios with three decimals.*

- BGB_{clump}: Clump biomass of rhizomes ($B_{rh\text{-}clump}$) (kg), clump biomass of coarse roots ($B_{co\text{-}clump}$) (kg), Clump biomass of fine roots ($B_{fi\text{-}clump}$) (kg) and BGB_{clump} (kg) = $B_{rh\text{-}clump} + B_{co\text{-}clump} + B_{fi\text{-}clump}$ (Table 14).

Table 14. Data set for developing BGB_{clump} models

Recorded by: Date:

Bamboo clump sample ID	D_{clump} (m)	H_{clump} (m)	N_{culm}	Fresh biomass of total rhizomes (kg)	Fresh biomass of total coarse roots (kg)	Fresh biomass of total fine roots (kg)	Ratio of rhizome	Ratio of coarse root	Ratio of fine root	Brh_{clump} (kg)	Bco_{clump} (kg)	Bfi_{clump} (kg)	BGB_{clump} (kg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14

Note: *Columns 1-7 are taken from Table 8; Columns 8-10 are taken from laboratory; Column 11 = Column 5 × Column 8; Column 12 = Column 6 × Column 9; Column 13 = Column 7 × Column 10; Column 14 = Sum of Columns 11-13. Record all variables with one decimal place except* N_{culm}. *Ratios with three decimals.*

- B_{li} (kg) per unit of area (Table 15)

Table 15. Data set for developing B_{li} models

Recorded by: Date:

Litter subplot sample ID	Fresh Bli (g)	LD (mm)	Fresh-to-dry litter mass ratio	B_{li} (kg) per ha
1	2	3	4	5

Note: *Columns 1-3 are taken from Table 9; Column 4 is taken from laboratory; Column 5 = Column 2 × Column 4. Record all variables with one decimal place.*

For example, a data set of *Bambusa procera* is created according to the destructive methods to develop and validate the allometric equations provided in Annex 1. Tools and equipment needed for data collection to set up the biomass and carbon model for a team are introduced in Annex 2.

6.3. Methods of fitting bamboo biomass modelling systems

6.3.1. Selection of predictors and response variables

i) For AGB_{bamboo} model

The response variables consist of B_{cu}, B_{br}, B_{le} and AGB. The predictor variables consist of D (Kumar, Rajesh and Sudheesh, 2005), or D and A (Zhuang et al, 2015), or D and H (Li, Lin and Yen, 2016) or a combination of covariates $D^2H = D^2 \times H$ (Yuen, Fung and Ziegler, 2017; Li, Lin and Yen, 2016; Ricardo et al, 2013; Yiping et al, 2010; Sohel et al, 2015).

ii) For AGB_{clump} model

The response variables consist of $B_{cu\text{-}clump}$, $B_{br\text{-}clump}$, $B_{le\text{-}clump}$ and AGB_{clump}. The predictor variables consist of D_{clump} (Kumar, Rajesh and Sudheesh, 2005), or D_{clump} and H_{clump}, or D_{clump}, H_{clump} and N_{culm}.

iii) For shrub biomass model ($AGB_{non\text{-}bamboo}$)

The response is $AGB_{non\text{-}bamboo}$. The predictors consist of the CA of shrub plant (CA, cm^2) and/or shrub height (H, cm) and/or shrub diameter at base of plant (D_0, mm) (Petrova et al, 2010; Pearson, Brown and Birdsey, 2007).

iv) For BGB_{bamboo} model:

The response variables include below-ground biomass of bamboo plant rhizomes (BGB_{rh}), below-ground biomass of bamboo plant coarse roots (BGB_{co}), below-ground biomass of bamboo plant fine roots (BGB_{fi}) and BGB_{bamboo}. The predictor variables consist of D (Yuen, Fung and Ziegler, 2017), or D and A, or D and H or a combination of covariates D^2H.

v) For BGB_{clump} model

The response variables consist of $B_{rh\text{-}clump}$, $B_{co\text{-}clump}$, $B_{fi\text{-}clump}$ and BGB_{clump}. The predictor variables consist of D_{clump}, or D_{clump} and H_{clump} or D_{clump}, H_{clump} and N_{culm}.

vi) For B_{li} model

The response is B_{li}. The predictor is LD (IPCC, 2003).

The predictors mentioned above for different models will be selected using cross-validation, which is introduced in the following section.

6.3.2. Selection of the model form

There are various models; however, the power function has been used for most of the biomass allometric equations (Picard et al, 2015; Huy et al, 2019a,b). Yuen, Fung and Ziegler (2017) introduced the power function as an appropriate model for estimating biomass of different bamboo species. In many cases of cross-validation of the different model forms, the power model has produced the best goodness of fit and the lowest values of statistical errors. Therefore, using power form should be encouraged for bamboo biomass allometric equations. The following is the general power model based on Kralicek et al (2017), Huy et al (2016a, 2016b, 2019a,b) and Huy, Poudel and Temesgen (2016):

$$Y_i = \alpha \times X_i^{\beta} + \varepsilon_i \quad (2)$$
$$\varepsilon_i \sim iid \ \mathcal{N}(0, \sigma_i^{2}) \quad (3)$$

where Y_i is the response(s) of the bamboo plant/clump biomass for the i^{th} sampled bamboo plant/clump; α and β are the fixed effect parameters of the model; and X_i is the predictor(s), such as A, D, D_{clump}, H, H_{clump}, N_{culm}, CA, D_0, LD or combinations of D^2H for the i^{th} sampled bamboo plant/clump; and ε_i is the random error associated with the i^{th} sampled bamboo plant/clump.

The variance function is as follows (Huy et al, 2016a, b; Huy, Poudel and Temesgen, 2016c):

$$\mathrm{Var}(\varepsilon_i) = \widehat{\sigma}^2 (v_i)^{2\delta} \tag{4}$$

where $\widehat{\sigma}^2$ is the estimated error sum of squares; v_i is the weighting variable (D, D^2H), associated with the ith sampled plant/clump; and δ is the variance function coefficient to be estimated.

6.3.3. Weighted vs non-weighted models

In biometrics, the relationship between the response of biomass and the predictor is generally non-linear and heteroscedastic (Picard, Saint-André and Henry, 2012; Sola et al, 2014a, 2014b). In other words, the variations in response increase with greater predictor values (Figure 14).

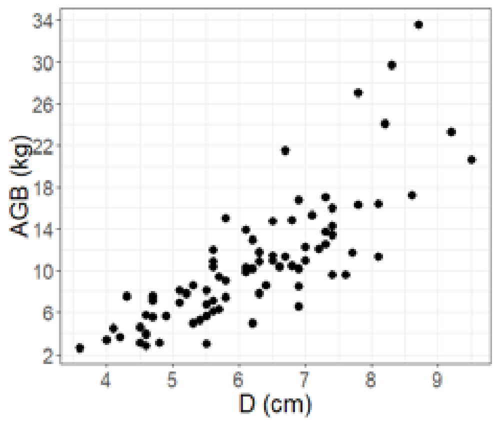
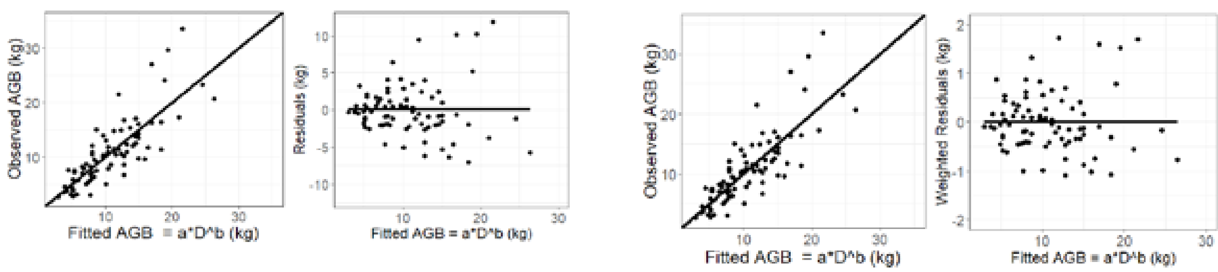


Figure 14. Allometric equation AGB_{bamboo} plant vs D is non-linear and heteroscedastic; the variability of AGB response increases with greater D predictor values.

Therefore, the weighted model fit should be employed to account for heteroscedasticity in residuals (Davidian and Giltinan, 1995; Huy et al, 2016a, 2016b, 2019a,b; Huy, Poudel and Temesgen, 2016). Weighted variables = $1/X^{2\delta}$, where X = D, D^2H and δ is the variance function coefficient to be estimated (Huy et al, 2019a,b).



Non-weighted model   Weighted model

Figure 15. Observed vs fitted values and residuals vs fitted values; non-weighted model; weighted model (left to right, respectively).

Figure 15 demonstrates the results of the comparisons between the two models with and without the weight variable. The results show that the weighted model improved heteroscedasticity in residuals and produced much lower residuals than did the non-weighted model. Thus, applying the weight to the biometric models can play an important role in improving reliability and reducing the uncertainty of the predicted forest biomass and carbon.

6.3.4. Model fit statistics and plot analysis to compare and select the best model

Some main important model fit statistics are usually used to evaluate, compare and select the best equations such as the following:

- The Akaike Information Criterion (AIC) (Akaike, 1973; Chave et al, 2005; Basuki et al, 2009; Picard, Saint-André and Henry, 2012; Huy et al, 2016a, 2016b, 2019a,b; Huy, Poudel and Temesgen, 2016) is used as a key statistic to compare and select the optimal models. The model that has the lowest AIC value is selected as the best model.

$$AIC = -2\ ln(L) + 2p \qquad (5)$$

where L is the likelihood of the model, and p is the number of the parameters of the model.

- Along with AIC, the determination coefficient of adj. R^2 is also used to assess the model performance; an adj. R^2 coefficient with *p*-value < 0.05 and closer to 1 is considered better.

- The parameter exists if the significance of *p*-value < 0.05.

- Diagnostic plots of the observed vs fitted values and the trend of residuals are also used to assess the model performance (Figure 16).

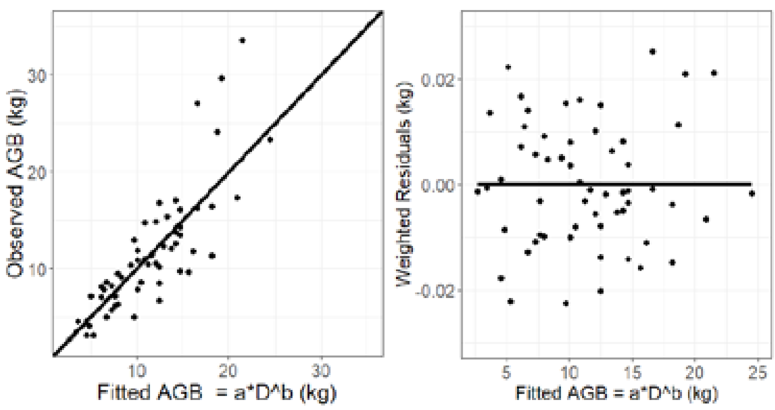


Figure 16. Observed vs fitted AGB values and weighted residuals vs fitted AGB values (left to right, respectively).

- One or more statistical errors should be used to evaluate the model, such as (per cent) bias, (per cent) Root Mean Squared Error (RMSE) and Mean Absolute (Per cent) Error (MAE/MAPE) (Mayer and Butler, 1993; Chave et al, 2005; Basuki et al, 2009; Huy et al, 2016a, 2016b, 2019a,b; Huy, Poudel and Temesgen, 2016). A model that has the lowest statistical error value is preferred as the best model:

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i) \quad (6)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (7)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (8)$$

$$Bias\ \% = \frac{100}{n}\sum_{i=1}^{n}\frac{(y_i - \hat{y}_i)}{(y_i)} \quad (9)$$

$$RMSE\ \% = 100\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i - \hat{y}_i}{y_i}\right)^2} \quad (10)$$

$$MAPE\ \% = \frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i} \quad (11)$$

- The Fit Index (FI) (Parresol, 1999; Huy et al, 2019a,b) can also be used to assess the goodness of fit of the models. The models that have larger FI values are preferred. The best model has its FI close to 1.

$$FI = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (12)$$

where, n is the number of the samples; y_i, $\hat{y}_i$ and $\bar{y}$ are the observed, fitted/predicted and averaged values for the i^{th} sample, respectively.

6.3.5. Weighted log-transformation model fit

The power form can be fit using log-transformed data linear regression (IPCC, 2003; Brown, 1997; Basuki et al, 2009; Chave et al, 2014). Kumar, Rajesh and Sudheesh (2005) and Yuen, Fung and Ziegler (2017) also used log transformation to fit a power model for *Bambusa nutans*. Setting up the model of log-transformation can be done simply in Microsoft Office Excel; however, Excel does not export the statistical errors to evaluate the model. Therefore, it is recommended to use open source software R, which is free software, with flexible and diverse use and easy application. College graduates who undergo a 3-5-day training course can afford to use R for modelling. A brief instruction of how to set up the R software and run it by using the R code is provided in Boxes in this manual (see Box 18 in Annex 3).

An 'lm' package in the R statistical software should be used to develop and evaluate a weighted log-transformation model. For example, a weighted log-transformation model below has been developed for a bamboo species (see the data set in Annex 1). The R code is introduced in Box 1.

$$log(AGB) = a + b \times log\ (D) \quad (13)$$

Box 1: R code to develop and evaluate a weighted log-transformation model: *log(AGB) = a + b × log (D)*

```
# Erase memory
rm(list=ls())

# Clean plot window
dev.off()

# Define the working directory
setwd("C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data")

# Import data
t <- read.table("tAll.txt", header=T,sep="\t",stringsAsFactors = FALSE)

length(t$AGB)

# Packages for plot analysis
library(ggplot2)
library(cowplot)
library(gridExtra)

# Modelling weighted log-transformation
t$logD = log(t$D)
logmodel <- lm(log(AGB)~log(D), data=t, weights = 1/log(D)^2)

# Output
summary(logmodel)

# Fitted and residuals values of the model
t$logmodel.fit <- fitted.values(logmodel)
t$logmodel.res <- residuals(logmodel)
t$logmodel.res_weight <- residuals(logmodel)/t$logD^2

# Calculation of correction factor: CF = exp(RSE^2/2)
summary(logmodel)$sigma^2
logmodel.CF <- exp(summary(logmodel)$sigma^2/2)
logmodel.CF

# Model back transformed: Y = CF*exp(a)*X^b
# Calculation of power model parameters
a <- exp(coefficients(logmodel)[1])
b <- coefficients(logmodel)[2]
a
b

# Calculation of fitted values and residuals back transformed
t$backtrans.fit <- logmodel.CF * a * t$D^b
t$backtrans.res <- t$AGB - t$backtrans.fit
t$backtrans.res_weight <- (t$AGB - t$backtrans.fit)/t$logD^2

# Adj. R square
R2 <- 1- sum((t$AGB - t$backtrans.fit)^2)/sum((t$AGB - mean(t$AGB))^2)
R2
R2.adjusted <- 1 - (1-R2)*(length(t$D)-1)/(length(t$D)-3-1)
R2.adjusted
```

```
# Calculation of AIC = -2L + 2*p where p is the number of parameters of the model
L <- -1/2*sum(t$backtrans.res^2/var(t$backtrans.res)+log(2*pi)
                    +log(var(t$backtrans.res)))

AIC.backtrans <- -2*L +2*2
AIC.backtrans

# Calculation of error statistics
Bias <- 100*mean(t$backtrans.res/t$AGB)
RMSE <- sqrt(mean((t$backtrans.res)^2))
MAPE <- 100*mean(abs(t$backtrans.res)/t$AGB)

Bias
RMSE
MAPE

# Plot of observed vs fitted values
p1 <- ggplot(t, aes(x=t$backtrans.fit , y=AGB))
p1 <- p1 + geom_point(cex=2)
p1 <- p1 + geom_abline(cex = 1.5, intercept = 0, slope = 1, col="black")
p1 <- p1 + xlab("Fitted AGB (kg)") + ylab("Observed AGB (kg)") + theme_bw()+ theme_bw()
p1 <- p1 + theme(axis.title.y = element_text(size = rel(1.5)))
p1 <- p1 + theme(axis.title.x = element_text(size = rel(1.5)))
p1 <- p1 + theme(plot.title = element_text(size = rel(1.7)))
p1 <- p1 + theme(axis.text.x = element_text(size=15))
p1 <- p1 + theme(axis.text.y = element_text(size=15))
p1 <- p1 + ylim(2.5,35)
p1 <- p1 + xlim(2.5,35)
p1

# Plot of residuals vs fitted values
summary(t$backtrans.res_weight)
p2 <- ggplot(t, aes(x=t$backtrans.fit, y=t$backtrans.res_weight)
p2 <- p2 + geom_point(cex = 2)
p2 <- p2 + geom_line(cex = 1.5, aes(x=t$backtrans.fit, y=0))
p2 <- p2 + xlab("Fitted AGB (kg)") + ylab("Weighted residuals (kg)") + theme_bw()+ theme_bw()
p2 <- p2 + theme(axis.title.y = element_text(size = rel(1.5)))
p2 <- p2 + theme(axis.title.x = element_text(size = rel(1.5)))
p2 <- p2 + theme(plot.title = element_text(size = rel(1.7)))
p2 <- p2 + theme(axis.text.x = element_text(size=15))
p2 <- p2 + theme(axis.text.y = element_text(size=15))
p2 <- p2 + ylim(-3, 3)
p2 <- p2 + xlim(2.5, 30)
p2

plot_grid(p1, p2, ncol = 2)

# The end
```

The result of modelling the weighted log-transformation is as follows:

Log-model with weight variable = $1/\log(D)^{0.9}$:

$$log(AGB) = -1.947 + 2.308 \times log(D). \quad (14)$$

Back transformation model:

$$AGB = CF \times 0.141 \times D^{2.315}, \quad (15)$$

where correction factor CF = 1.016. The statistics of the model: R^2 adj. = 0.650; AIC = 449; Bias % = -6.5%; RMSE = 3.5 kg and MAPE = 25.6%.

The plots in Figure 17 show observed vs fitted AGB values and the residuals vs fitted AGB values.

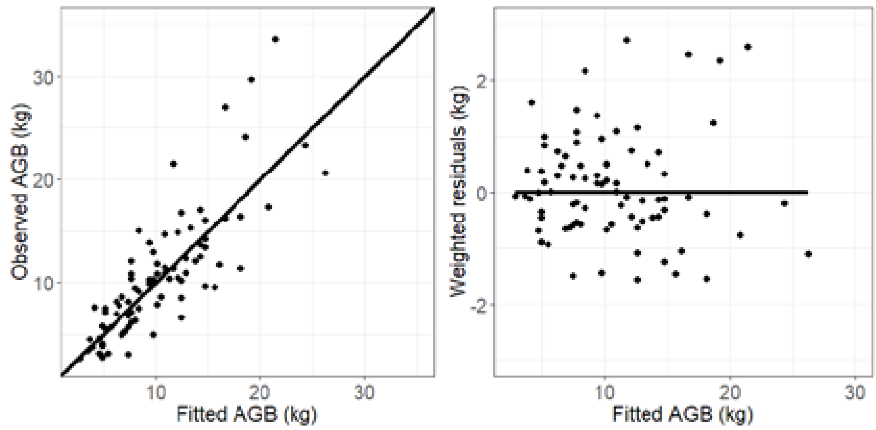


Figure 17. Plot of log-transformed linear model $log(AGB) = a + b \times log(D)$; observed vs fitted AGB values; residuals vs fitted AGB values (left to right, respectively).

6.3.6. Weighted non-linear fixed effect model fit by maximum likelihood

The power equation can be fit in two ways: (a) as a linear model of the log-transformed data, introduced above, or (b) as a non-linear mode. Huy, Poudel and Temesgen (2016) compared the log-linear and non-linear models using Furnival Index (FurI) (Furnival, 1961) and showed that non-linear power equation fit produced higher reliability. Therefore, the method of a weighted non-linear fixed effect model fit by maximum likelihood is recommended to fit the biomass model for bamboo.

In this case, the 'nlme' packages in statistical software R should be used (R Core Team, 2018; Bates, 2010; Pinheiro et al, 2014). For example, consider using R to develop and evaluate a power model for a bamboo species (see the data set in Annex 1). The R code is introduced in Box 2. The power model form is as follows:

$$AGB = \alpha \times D^{\beta}. \quad (16)$$

Box 2. R code of weighted non-linear fixed effect model fit by maximum likelihood to develop and evaluate power model: $AGB = \alpha \times D^{\beta}$

```
# Clean plot window
dev.off()

# Define the working directory
```

```
setwd("C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data")

# Import data
t <- read.table("tAll.txt", header=T,sep="\t",stringsAsFactors = FALSE)

# Packages for plot analysis
library(ggplot2)
library(nlme)
library(cowplot)
library(gridExtra)

# Modelling
start <- coefficients(lm(log(AGB)~log(D), data=t))
names(start) <- c("a","b")
start[1]<-exp(start[1])

Max_like <- nlme(AGB~a*D^b, data=cbind(t,g="a"), fixed=a+b~1,
                 start=start, groups=~g, weights=varPower(form=~D))

# Output of the model
summary(Max_like)

# Calculation of fitted and residual values
k <- summary(Max_like)$modelStruct$varStruct[1]
t$Max_like.fit <- fitted.values(Max_like)
t$Max_like.res <- residuals(Max_like)
t$Max_like.res.weigh <- residuals(Max_like)/t$D^k

# Calculation of AIC, R2
AIC <- AIC(Max_like)
AIC
R2 <- 1- sum((t$AGB - t$Max_like.fit)^2)/sum((t$AGB - mean(t$AGB))^2)
R2.adjusted <- 1 - (1-R2)*(length(t$D)-1)/(length(t$D)-3-1)
R2.adjusted

# Calculation of error statistics
Bias = 100*mean((t$Max_like.res)/t$AGB)
RMSE = sqrt(mean(t$Max_like.res^2))
MAPE = 100*mean(abs(t$Max_like.res)/t$AGB)

Bias
RMSE
MAPE

# Plot of observed vs fitted values
p1 <- ggplot(t)
p1 <- p1 + geom_point(aes(x=Max_like.fit, y=AGB), cex = 2)
p1 <- p1 + geom_abline(intercept = 0, slope = 1, col="black", cex=1.5)
p1 <- p1 + xlab("Fitted AGB  = a*D^b (kg)") + ylab("Observed AGB (kg)") + theme_bw()
p1 <- p1 + labs(title = "")
p1 <- p1 + theme(axis.title.y = element_text(size = rel(1.7)))
p1 <- p1 + theme(axis.title.x = element_text(size = rel(1.7)))
p1 <- p1 + theme(plot.title = element_text(size = rel(1.7)))
p1 <- p1 + theme(axis.text.x = element_text(size=15))
p1 <- p1 + theme(axis.text.y = element_text(size=15))
```

```
p1 <- p1 + ylim(2.5,35)
p1 <- p1 + xlim(2.5,35)
p1

# Plot of weighted residuals vs fitted values
p2 <- ggplot(t)
p2 <- p2 + geom_point(aes(x=Max_like.fit, y=Max_like.res.weigh), cex = 2)
p2 <- p2 + geom_line(cex = 1.5, aes(x=Max_like.fit, y=0))
p2 <- p2 + xlab("Fitted AGB = a*D^b (kg)") + ylab("Weighted Residuals (kg)") + theme_bw()
p2 <- p2 + labs(title = "")
p2 <- p2 + theme(axis.title.y = element_text(size = rel(1.5)))
p2 <- p2 + theme(axis.title.x = element_text(size = rel(1.5)))
p2 <- p2 + theme(plot.title = element_text(size = rel(1.7)))
p2 <- p2 + theme(axis.text.x = element_text(size=15))
p2 <- p2 + theme(axis.text.y = element_text(size=15))
p2 <- p2 + ylim(-0.2, 0.2)
p2 <- p2 + xlim(2.5, 35)
p2

plot_grid(p1, p2, ncol = 2)

# The end
```

The result of the weighted non-linear model is as follows:

Power model:

$$AGB = 0.152 \times D^{2.294}. \quad (17)$$

The statistics of the model: R^2adj. = 0.653; AIC = 424; Bias % = -9.8; RMSE = 3.5 kg and MAPE = 26.6%.

The plots in Figure 18 show the observed vs fitted AGB values and residuals vs fitted AGB values.

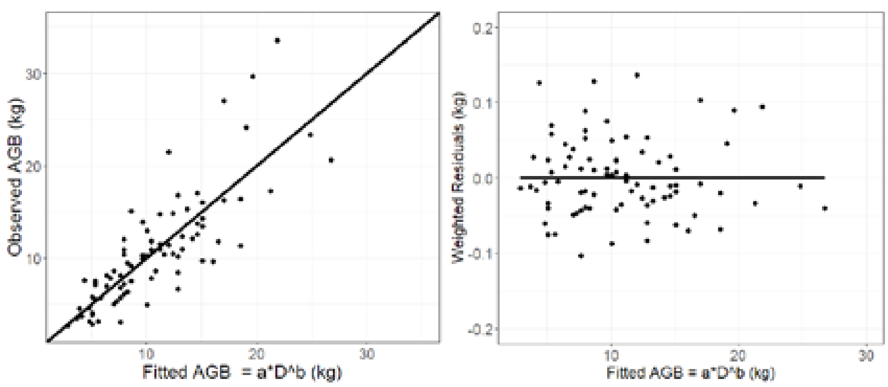


Figure 18. Plot of weighted non-linear model $AGB = \alpha \times D^{\beta}$; observed vs fitted AGB values; weighted residuals vs fitted AGB values (left to right, respectively).

6.3.7. Log-transformation vs non-linear fit

Most power models for estimating forest tree biomass in pantropical regions have been performed using log-transformation (IPCC, 2003; Brown, 1997; Basuki et al, 2009; Chave et al, 2014). Kumar, Rajesh and Sudheesh (2005) and Yuen, Fung and Ziegler (2017) also used log-log transformation to fit the power model for *Bambusa nutans*. Huy, Poudel and Temesgen (2016) used non-linear fit to develop the models for AGB estimates in tropical forests; they compared the log-linear and non-linear equations using FurI (Furnival, 1961; Jayaraman, 1999) and figured out that a non-linear power law fit produced higher reliability. However, we should choose the right method to fit the power law to be able to produce higher reliability. Thus, we should use FurI (Furnival, 1961). A fit method that has a lower FurI value is considered the better method. The formula for FurI calculation is as follows (Huy, 2017a):

$$FurI = RMSE \times \frac{1}{Geometric\ mean\ (y')} \tag{18}$$

where *RMSE* is Root Mean Squared Error, and *y'* is the first derivative of y and equal to 1 if the response of log(y) is equal to 1/y.

For example, we can consider using FurI to compare two method fits of log-transformation $log(AGB) = a + b \times log(D)$ with non-linear $AGB = \alpha \times D^{\beta}$. The data set of a bamboo species in Annex 1 is used to examine the different method fits. The R code for this purpose is introduced in Box 3.

Box 3. R code for calculating FurI in case of weighted log-transformation and non-linear fits: $log(AGB) = a + b \times log(D)$ vs $AGB = \alpha \times D^{\beta}$

```
# Model: log(AGB) = a + b*log(D) - Weighted log-transformation linear fit
# Erase memory
rm(list=ls())

# Clean plot window
dev.off()

# Define the working directory
setwd("C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data")

# Import data
t <- read.table("tAll.txt", header=T,sep="\t",stringsAsFactors = FALSE)

# Install packages
library(ggplot2)
library(nlme)

# Modelling
logmodel <- lm(log(AGB)~log(D), data=t, weights = 1/log(D))

# Outputs of the model
summary(logmodel)
t$logD = log(t$D)
t$logmodel.fit <- fitted.values(logmodel)
t$logmodel.res <- residuals(logmodel)
t$logmodel.res.weight <- residuals(logmodel)/t$logD

# Furnival Index (FurI)= RMSE*(1/Geometric Mean of ln(y)'), ln(y)' = 1/y; Geometric Mean (gm):
gm = exp(mean(log(1/t$AGB)))
```

```
RMSE = sqrt(mean(t$logmodel.res^2))
FurI = RMSE*(1/gm)
FurI

# The end

# Model: AGB = a*D^b - Weighted non-linear fit
# Erase memory
rm(list=ls())

# Clean plot window
dev.off()

# Define the working directory
setwd("C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data")

# Import data
t <- read.table("tAll.txt", header=T,sep="\t",stringsAsFactors = FALSE)

# Install packages
library(ggplot2)
library(nlme)

# Modelling
start <- coefficients(lm(log(AGB)~log(D), data=t))
names(start) <- c("a","b")
start[1]<-exp(start[1])

Max_like <- nlme(AGB~a*D^b, data=cbind(t,g="a"), fixed=a+b~1,
            start=start, groups=~g, weights=varPower(form=~D))

# Outputs of the model
summary(Max_like)
k <- summary(Max_like)$modelStruct$varStruct[1]
k
t$Max_like.fit <- fitted.values(Max_like)
t$Max_like.res <- residuals(Max_like)
t$Max_like.res.weigh <- residuals(Max_like)/t$D^k

# Calculation of R2
R2 <- 1- sum((t$AGB - t$Max_like.fit)^2)/sum((t$AGB - mean(t$AGB))^2)
R2
R2.adjusted <- 1 - (1-R2)*(length(t$D)-1)/(length(t$D)-3-1)
R2.adjusted

# Furnival Index (FurI)= RMSE*(1/Geometric Mean of y'), y' = 1; Geometric Mean (gm) = 1:
gm = exp(mean(log(1)))
RMSE = sqrt(mean(t$Max_like.res.weigh^2))
FurI = RMSE*(1/gm)
FurI

# The end
```

Thus, the weighted non-linear fit by maximum likelihood that produced significantly lower FurI values than the weighted log-transformation linear fit is considered a better fit (Table 16).

Table 16. Using FurI to compare two fit methods for power model: weighted log-transformation linear and weighted non-linear fits

Model	Fit method	Weight variable	Adj. R^2	FurI
$log(AGB) = a + b \times log(D)$	Weighted log-transformation linear	1/log(D)	0.720	2.79
$AGB = \alpha \times D^{\beta}$	Weighted non-linear maximum likelihood	$1/D^{\delta}$	0.653	0.05

Note: *δ is the variance function coefficient.*

6.3.8. Weighted non-linear mixed effect model fit by maximum likelihood

Yuen, Fung and Ziegler (2017) found that carbon sequestration depends on the species of bamboo, environmental conditions and management techniques, such as rainfall, temperature, plant density and age. Weighted non-linear mixed effects models fit by maximum likelihood can be used to determine the random effects of ecological and forest stand factors (Bates, 2010; Pinheiro et al, 2014). Mixed effects models fit uses the 'nlme' packages in the statistical software R (R Core Team, 2018). The form of the allometric equation, after Huy et al (2016a), is as follows:

$$Y_{ij} = (\alpha + a_i) \times X_{ij}^{(\beta + b_i)} + \varepsilon_{ij} \quad (19)$$

$$\varepsilon_{ij} \sim iid\ \mathcal{N}(0, \sigma^2) \quad (20)$$

where Y_{ij} is the AGB in kg for the j^{th} bamboo plant from the i^{th} class of a factor; α and β are the fixed effects parameters of the model; a_i and b_i are parameters associated with i^{th} class of a factor; X_{ij} is the covariate D (cm), H (m) or D^2H for the j^{th} plant in i^{th} class of a factor; and ε_{ij} is the random error associated with the j^{th} plant from the i^{th} class of a factor.

The variance function is determined as follows:

$$\text{Var}(\varepsilon_{ij}) = \widehat{\sigma^2}(v_{ij})^{2\delta} \quad (21)$$

where $\widehat{\sigma^2}$ is the estimated error sum of squares; v_{ij} is the weighting variable (D or D^2H), associated with the j^{th} bamboo plant from the i^{th} class of the random effect factor; and δ is the variance function coefficient to be estimated. The usefulness of the random effects of the ecological and forest stand factors is determined based on a significant change in the parameters.

For bamboo forests, the random effects of forest stand and environmental factors such as the age of the bamboo culm (A, year), density of the bamboo culm (N), altitude, rainfall, slope and soil unit can be tested. The following is an example of the random effect of the slope on model $AGB = \alpha \times D^{\beta}$ for *Bambusa procera* using the data set in Annex 1. The R code for the model with random effect is shown in Box 4.

Box 4. R code for weighted non-linear mixed effects model with random effects fit by maximum likelihood. Model: $AGB = \alpha \times D^{\beta}$

```
# Erase memory
rm(list=ls())
# Clean plot window
dev.off()

# Define the working directory
setwd("C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data")
# Import data
t <- read.table("tAll.txt", header=T,sep="\t",stringsAsFactors = FALSE)

# Install packages
library(ggplot2)
library(nlme)
library(cowplot)
library(gridExtra)

# Modelling with random effect
start <- coefficients(lm(log(AGB)~log(D), data=t))
names(start) <- c("a","b")
start[1]<-exp(start[1])

Randomeffect <- nlme(AGB~a*D^b, data=t, fixed=a+b~1, random=b~1,
        start=start, groups=~Slope_class, weights=varPower(form=~D))

# Output of model
summary(Randomeffect)
k <- summary(Randomeffect)$modelStruct$varStruct[1]
k

# Parameters and random parameters
fixef(Randomeffect)
ranef(Randomeffect)
coef((Randomeffect))

# Standard errors of random parameters
Sdi = ranef(Randomeffect, standard= TRUE)
Si = ranef(Randomeffect)/Sdi
SEi = Si/sqrt(table(t$Slope_class))
SEi
table(t$Slope_class)

# Fitted and residual values of the model
t$Randomeffect.fit <- fitted.values(Randomeffect)
t$Randomeffect.res <- residuals(Randomeffect)
t$Randomeffect.res.weigh <- residuals(Randomeffect)/t$D^k

# Calculation of AIC, R2
AIC(Randomeffect)
AIC
R2 <- 1- sum((t$AGB - t$Randomeffect.fit)^2)/sum((t$AGB - mean(t$AGB))^2)
R2.adjusted <- 1 - (1-R2)*(length(t$D)-1)/(length(t$D)-3-1)
R2.adjusted
```

```
# Calculation of statistical errors
Bias = 100*mean((t$Randomeffect.res )/t$AGB)
RMSE = sqrt(mean(t$Randomeffect.res ^2))
MAPE = 100*mean(abs(t$Randomeffect.res )/t$AGB)

Bias
RMSE
MAPE

# Plot AGB vs D2H with random effect of slope
p <- ggplot(t)
p <- ggplot(t, aes(x=D2H, y=AGB, pch=Slope_class))
p <- p + geom_point(cex=3)
p <- p + geom_line(cex = 2.5, aes(x=D2H, y=Randomeffect.fit, linetype=Slope_class))
p <- p + xlab("D") + ylab("AGB (kg)") + theme_bw()
p <- p + theme(legend.title=element_blank())
p <- p + labs(title = "")
p = p + theme(axis.title.y = element_text(size = rel(1.7)))
p = p + theme(axis.title.x = element_text(size = rel(1.7)))
p <- p + theme(plot.title = element_text(size = rel(1.7)))
p = p + theme(axis.text.x = element_text(size=15))
p = p + theme(axis.text.y = element_text(size=15))
p = p + theme(legend.position=c(.3, .8))
p = p + theme(legend.text = element_text(size=18))
p = p + ylim(0,35)
p = p + xlim(100,1800)
p

# The end
```

Thus, the slope significantly affected the model $AGB = \alpha \times D^{\beta}$; the random effects of the model produced better statistics than did the model without random effects (Table 17). The changes in parameters and standard errors were estimated for the model with random effects presented in Table 18, and Figure 19 demonstrated a fitted AGB distinguishing among the classes of the slope factor.

Table 17. Comparison of random effects of the slope with selected model without random effects; selected model: $AGB = \alpha \times D^{\beta}$

Random effect	Weight variable	AIC	Adj. R^2
None	$1/D^{\delta}$	424	0.653
Slope	$1/D^{\delta}$	406	0.750

Table 18. Parameters and standard errors estimated for weighted non-linear mixed effects model with random effects of slope class for the form $AGB = \alpha \times D^{\beta}$

Random effect	Class	Parameters		Standard error		Number of bamboo plant samples
		α	B	α	β	
Slope	Slope1 ≤ 10°	0.16208	2.14309	0.04019	0.02250	19
	Slope2 = 11-30°	0.16208	2.26756	0.04019	0.01400	49
	Slope3 = > 30°	0.16208	2.37151	0.04019	0.02532	15

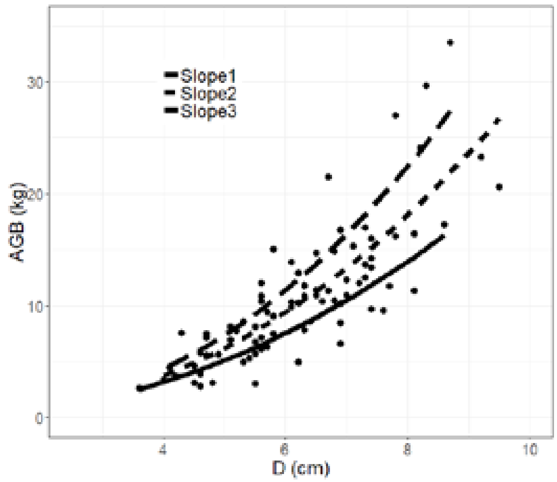


Figure 19. Fitted model $AGB = \alpha \times D^{\beta}$; distinguished among classes of the slope factor vs observation of the data set.

6.3.9. Seemingly Unrelated Regression (SUR)

The biomass plant component models (e.g. B_{cu}, B_{br}, B_{le}, AGB_{bamboo} and BGB_{bamboo}) and the total (TB_{bamboo}) model, which all fit independently, can be used; the TB_{bamboo}, which is calculated from the component models, is different from the estimates obtained from the TB_{bamboo} model. SUR can compensate for this limitation by allowing simultaneous estimates of the component biomass as well as TB_{bamboo}. SUR also considers the correlation among equations to ensure the additivity of predictions (Parresol, 2001; Sanquetta et al, 2015; Poudel and Temesgen, 2016; Kralicek et al, 2017; Gonzalez-Benecke et al, 2018; Huy et al, 2019a,b). The weighted non-linear SUR can be implemented using the Statistical Analysis System (SAS) procedure Proc Model with the generalised least squares method (SAS Institute Inc., 2014).

Below is a modelling system to simultaneously estimate plant TB_{bamboo} and its components, which is based on the general form suggested by Parresol (2001), Poudel and Temesgen (2016), Kralicek et al (2017) and Huy et al (2019a,b):

$$Bcu = a_1 \times X_1^{b1} + \varepsilon_1 \quad (22)$$

$$Bbr = a_2 \times X_2^{b_2} + \varepsilon_2 \quad (23)$$

$$Ble = a_3 \times X_3^{b3} + \varepsilon_3 \quad (24)$$

$$BGB_{bamboo} = a_4 \times X_4^{b4} + \varepsilon_4 \quad (25)$$

$$TBbamboo = AGBbamboo + BGBbamboo = Bcu + Bbr + Ble + BGBbamboo = a_1 \times X_1^{b1} + a_2 \times X_2^{b_2} + a_3 \times X_3^{b_3} + a_4 \times X_4^{b4} + \varepsilon_5 \quad (26)$$

where B_{cu}, B_{br}, B_{le}, AGB_{bamboo}, BGB_{bamboo} and TB_{bamboo} are biomass of culms, branches, leaves, bamboo plant aboveground and belowground biomass and total in kg, respectively; a_i and b_i are parameters of the power model i (i = 1, 2, 3, 4 for culms, branches, leaves and belowground biomass, respectively); X_i is the predictor variable or combination of predictor variables (*D*, *H* or D^2H) for the i^{th} equation; and ε_i is the residuals for the i^{th} equation (i = 1, 2, 3, 4, 5). The weighting function is $1/X_i^{2\delta}$ (Picard, Saint-André and Henry, 2012) with δ, which is the variance function coefficient to be estimated.For example, a modelling system to simultaneously estimate plant AGB_{bamboo} and its components for a bamboo species (see the data set in Annex 1) has been developed and evaluated using the weighted non-linear SUR in SAS. The SAS code is introduced in Box 5.

Box 5. SAS code for weighted non-linear SUR to fit the modelling system for simultaneously estimating bamboo plant AGB and its components

```
dm'log;clear;output;clear';
options pageno=1 nodate nocenter;

/* Create a path to the folder where *.csv data is stored*/
%let infile_path  = C:\Users\baohu\OneDrive\1 - Bamboo INBAR\R code and Data\;
data AllData;
  infile "&infile_path.Bamboo.csv" dlm=',' firstobs=2 dsd truncover;
  input Plot_Code$ ID$ FT$ Tree_Code$ D H A Bcu Bbr Ble AGB Ccu Cbr Cle CAGB D2H;

run;

/* SUR:
/* Model Bcu Bbr Ble and AGB */
/* Parms based on models fitting results outside of SUR (coded in R)*/
/* Change Weight variables to have optimise Error of the System */
proc model data=AllData;
parms   a1=0.024 b1=0.892
a2=0.020 b2=0.728
a3=0.029 b3=0.513;

  Bcu = a1*(D2H**b1);
  h.Bcu = 1/D2H;
  Bbr = a2*(D2H**b2);
  h.Bbr = 1/D2H;
  Ble = a3*(D2H**b3);
  h.Ble = 1/D2H;
  AGB  = a1*(D2H**b1) + a2*(D2H**b2) + a3*(D2H**b3);
  h.AGB = 1/D2H;
  fit Bcu Bbr Ble AGB / sur outest = AllData_est;

run;
quit;
proc print data = AllData_est;
run;

*/ The end */
```

Table 19 presents the modelling system fit by SUR. Poudel and Temesgen (2016) and Huy et al (2019a,b) discovered that using a simultaneously developed modelling system reduced the errors in biomass prediction compared to the models fitted independently. Therefore, the authors recommended the SUR method for developing the biomass modelling systems.

Table 19. SUR method for determining the parameters of modelling systems to simultaneously estimate AGB_{bamboo} and its components for bamboo species

Model form	Weight variable	Parameter	Estimate ± Approx. std error	RMSE (kg)	Adj. R^2
$B_{cu} = a_1 \times (D^2H)^{b1}$	$1/D^2H$	a_1 b_1	0.02547 ± 0.00313 0.89510 ± 0.01770	2.93	0.634
$B_{br} = a_2 \times (D^2H)^{b2}$	$1/D^2H$	a_2 b_2	0.02457 ± 0.00916 0.69888 ± 0.05420	0.83	0.494
$B_{le} = a_3 \times (D^2H)^{b3}$	$1/D^2H$	a_3 b_3	0.01350 ± 0.00527 0.63191 ± 0.05700	0.25	0.517
$AGB = B_{cu} + B_{br} + B_{le} = a_1 \times (D^2H)^{b1} + a_2 \times (D^2H)^{b2} + a_3 \times (D^2H)^{b3}$	$1/D^2H$	$a_1, b_1\ a_2\ b_2$ $a_3\ b_3$	Idem	3.64	0.647

6.4. Cross-validation

To evaluate the uncertainty and reliability of the models, cross-validation is recommended for the application. Cross-validation is employed for model selection, evaluation and comparison. There are three popular cross-validation methods: Leave one out (LOOCV), K-Fold and Monte Carlo (Huy, 2017a, 2017b; Huy et al, 2019a,b). The Monte Carlo method is generalised and provides stable statistics based on large random realisations. Therefore, this manual introduces the application of Monte Carlo cross-validation.

According to Monte Carlo method, the data set is randomly split into two parts, with approximately 70-80 per cent for model development and 20-30 per cent for cross-validation, repeated n times (about 200 times) to reach stable statistics; the statistics of the model and the cross-validation errors are computed for each realisation of randomly selected data and averaged over the n (about 200) realisations (Temesgen, Zhang and Zhao, 2014; Huy et al, 2016a, 2016b; Huy, Poudel and Temesgen, 2016; Huy et al, 2019a,b). Models are compared and selected based on AIC (Akaike, 1973), adj. R^2, the significance of parameters which are obtained from 70 per cent of the randomly split data and averaged over the n (about 200) realisations; and diagnostic plots to examine the trend of residuals with increasing predictors (Yuen, Fung and Ziegler, 2017; Huy et al, 2019a,b). The model with the lowest AIC value is selected as the best model.

Cross-validation statistics of the models using bias (%), RMSE and MAPE (%) which are defined from the remaining 30 per cent of the randomly split data and averaged over the n (about 200) realisations (Huy et al, 2016a, 2016b; Huy, Poudel and Temesgen, 2016; Kralicek et al, 2017; Huy et al, 2019a,b). The model with smaller values of cross-validation errors is preferred.

$$Bias\ (\%) = \frac{1}{R}\sum_{r=1}^{R} \frac{100}{n}\sum_{i=1}^{n} \frac{y_i - \hat{y}_i}{y_i} \qquad (27)$$

$$RMSE = \frac{1}{R}\sum_{r=1}^{R}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (28)$$

$$MAPE\ (\%) = \frac{1}{R}\sum_{r=1}^{R}\frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i} \quad (29)$$

where, R is the number of realisations (about 200); n is the number of bamboo plant samples per realisation R; and y_i, $\hat{y}_i$ are the observed and predicted biomass for the i^{th} bamboo plant in realisation R, respectively. Finally, the parameters of the selected model are obtained by fitting the equation with the entire data set.For example, cross-validation is used to compare model $AGB = a \times D^b$ with $AGB = a \times D^b \times H^c$ to select the best model of biomass plant AGB_{bamboo} of a bamboo species in tropical forests based on the data set in Annex 1. The R code for Monte Carlo cross-validation is introduced in Box 6. In this example, the data set is randomly split into two parts, with 80 per cent for model development and 20 per cent for cross-validation, repeated 200 times.

Box 6. R code for Monte Carlo cross-validation of weighted non-linear fixed model fit by maximum likelihood for model $AGB = a \times D^b \times H^c$

```
# Erase memory
rm(list=ls())

# Clean plot window
dev.off()

# Define the working directory
setwd("C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data")

# Import data
t <- read.table("tAll.txt", header=T,sep="\t",stringsAsFactors = FALSE)

# Install vpackages
library(ggplot2)
library(nlme)
library(cowplot)
library(gridExtra)

# Model: AGB = a*D^b*H^c
AIC = rep(0, 200)
R2adj = rep(0, 200)
RMSE = rep(0, 200)
Bias = rep(0, 200)
MAPE = rep(0, 200)

# Realisations of 200 times
for(i in 1:200){

# Randomly split data set: 80 per cent data set for development of equation and 20 per cent for validation
t_eq <- t[sample(nrow(t), length(t$D)*0.8), ]
n_va <- t[!t$ID %in% t_eq$ID, ]

# Modelling
start <- coefficients(lm(log(AGB)~log(D)+log(H), data=t_eq))
names(start) <- c("a","b","c")
start[1]<-exp(start[1])
```

```
Max_like <- nlme(AGB~a*D^b*H^c, data=cbind(t_eq,g="a"), fixed=a+b+c~1,
            start=start, groups=~g, weights=varPower(form=~D))

# Fitted values and residual
k <- summary(Max_like)$modelStruct$varStruct[1]
t_eq$Max_like.fit <- fitted.values(Max_like)
t_eq$Max_like.res <- residuals(Max_like)
t_eq$Max_like.res.weigh <- residuals(Max_like)/t_eq$D^k

# Calculation of AIC, R2
AIC[i] <- AIC(Max_like)
R2 <- 1- sum((t_eq$AGB - t_eq$Max_like.fit)^2)/sum((t_eq$AGB - mean(t_eq$AGB))^2)
R2.adjusted <- 1 - (1-R2)*(length(t_eq$D)-1)/(length(t_eq$D)-4-1)
R2adj[i] <- R2.adjusted

# Predicted values
n_va$Pred <- predict(Max_like, newdata=cbind(n_va,g='a'))

# Calculation of Bias, RMSE, MAPE%:
Bias[i] = 100*mean((n_va$AGB - n_va$Pred)/n_va$AGB)
RMSE[i] = sqrt(mean((n_va$AGB - n_va$Pred)^2))
MAPE[i] = 100*mean(abs(n_va$AGB - n_va$Pred)/n_va$AGB)

}
i
# Mean of AIC, R2 adj.:
mean(AIC)
mean(R2adj)

# Mean of Bias%, RMSE, MAPE%
mean(Bias)
mean(RMSE)
mean(MAPE)

# Output of model:
summary(Max_like)

# Plot of weighted residuals vs fitted values
summary(t_eq$Max_like.res.weigh)
p <- ggplot(t_eq)
p <- p + geom_point(aes(x=Max_like.fit, y=Max_like.res.weigh), cex = 2)
p <- p + geom_line(cex = 1.5, aes(x=Max_like.fit, y=0))
p <- p + xlab("Fitted AGB = a*D^b*H^c (kg)") + ylab("Weighted Residuals (kg)") + theme_bw()
p <- p + labs(title = "")
p <- p + theme(axis.title.y = element_text(size = rel(1.5)))
p <- p + theme(axis.title.x = element_text(size = rel(1.5)))
p <- p + theme(plot.title = element_text(size = rel(1.7)))
p <- p + theme(axis.text.x = element_text(size=15))
p <- p + theme(axis.text.y = element_text(size=15))
p <- p + ylim(-0.2, 0.2)
p <- p + xlim(2.5, 25)
p

# The end
```

In this example, the model with predictors of *D* and *H* gave slightly better cross-validation statistics than did the model with *D* predictor only (Table 20). The diagnostic of the weighted residuals plot in Figure 20 also showed that model $AGB = a{\times}D^b{\times}H^c$ has lower and narrower variable residuals along with fitted *AGB* than has model $AGB = a{\times}D^b$; however, the model with *D* and *H* predictors with *H* variable parameter has a *p*-value > .05. Therefore, model $AGB = a{\times}D^b$ should be considered and selected.

Table 20. Cross-validation of different AGB_{bamboo} models for bamboo species

Model form	Bias (%)	RMSE (kg)	MAPE (%)
$AGB = a \times D^b$	-10.9	3.6	27.7
$AGB = \alpha \times D^b \times H^{c*}$	-8.8	3.5	26.9

Note: **Parameter with **p**-value > .05.*

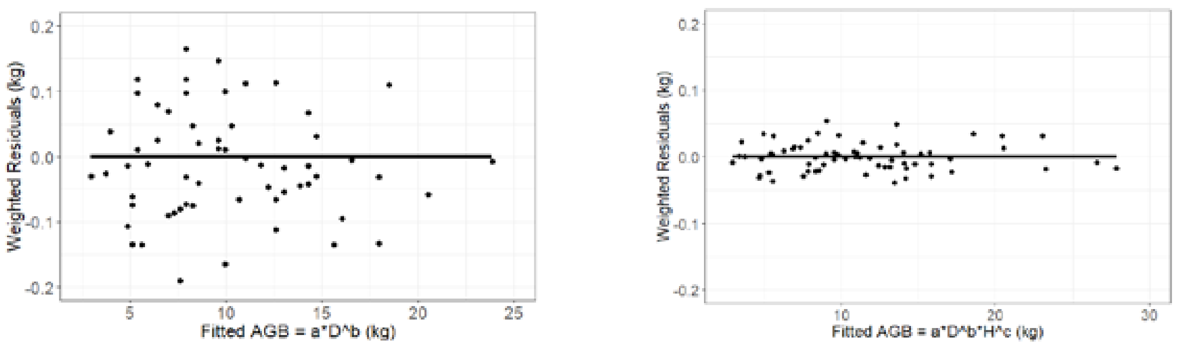


Figure 20. Plots of weighted residuals vs fitted *AGB* for two models: $AGB = a{\times}D^b$ and $AGB = a{\times}D^b{\times}H^c$ (left to right, respectively).

7. Validation of existing bamboo allometric equations worldwide

There are very few bamboo biomass equations. Most of the models have been developed in China, India, Japan and Taiwan (Isagi, Kawahara and Ito, 1997; Yuen, Fung and Ziegler, 2017). The preparation of biomass and carbon models plays an important role in supporting the inventory of bamboo forest carbon. Thus, it is necessary to continue developing models for bamboo plants. However, as the development of the biometrics is usually costly due to the application of destructive method, try to use the models available. Table 21 offers a list of the existing allometric equations for estimating bamboo biomass.

Priority should be given to the selection of models for the same species or the same genus with the locality, followed by the same ecological conditions. Next, it is necessary to appraise the misuse using error statistics, such as Bias%, RMSE, MAPE% and reliability as the FI assessment to real local data. To implement the evaluation model available, it is necessary to collect destructively biomass data of at least 30-50 plants in a site. After completing the data collection and analysis introduced above, proceed with the independent validation by calculating error statistics and the FI by applying the model to the local data set. The model with a low value of errors and great FI values (close to 1) is appropriate for the on-site application.

Table 21. Existing allometric equations for estimating bamboo plant/clump B_{cu}, AGB, BGB and TB of some bamboo species in some regions

ID	Bamboo species	Author(s) (year)	Location, region	Model	N (number of sampled bamboos)	R^2	Error statistics
1.	*Bambusa balcooa*	Nath, Das and Das (2009)	Barak Valley, India	$log(AGB) = 2.476 + 0.997 \times log(D)$	NA	0.670	NA
2.	*Bambusa bambos*	Shanmughavel and Francis (1996)	Kallipatty, India	$log(AGB) = -0.3003 + 0.6804 \times log(D) + 1.0440 \times log(H)$	NA	0.990	NA
3.	*Bambusa bambos*	Kumar, Rajesh and Sudheesh (2005)	Kerala	$AGB_{clump} = -3225.8 + 1730.4 \times D_{clump}$	8	0.830	NA
4.	*Bambusa bambos*	Shanmughavel and Francis (1996 cited Yuen, Fung and Ziegler, 2017)	India	$BGB = 0.780 \times D^{0.708}$	90	0.554	NA
5.	*Bambusa bambos*	Shanmughavel and Francis (1996 cited Yuen, Fung and Ziegler, 2017)	India	$Bcu = 0.287 \times D^{3.524}$	NA	0.938	NA

ID	Bamboo species	Author(s) (year)	Location, region	Model	N (number of sampled bamboos)	R^2	Error statistics
6.	*Bambusa cacharensis*	Nath, Das and Das (2009)	Barak Valley, India	$log(AGB) = 2.114 + 1.087 \times log(D)$	NA	0.710	NA
7.	*Bambusa genus*	Melo et al (2015)	Brazil	$AGB = -0.5699 + 0.67696 \times D^{0.5} \times log(D)$	24	0.980	NA
8.	*Bambusa nutans*	Yuen, Fung and Ziegler (2017)	Thailand	$AGB = 0.269 \times D^{2.107}$	65	0.667	NA
9.	*Bambusa procera*	Huy et al (2019b)	Vietnam	$AGB = Bcu + Bbr + Ble = 0.09814\ D^{2.36569} + 0.05216\ D^{2.00483} + 0.03044\ D^{1.74187}$	83	0.627 0.567 0.536 0.657	RMSE = 2.96, 0.77, 0.25, 3.58
10.	*Bambusa procera*	Huy et al (2019b)	Vietnam	$AGB = Bcu + Bbr + Ble = 0.02269\ (D^2H)^{0.90703} + 0.02015\ (D^2H)^{0.72251} + 0.03420\ D^{1.67330}$	83	0.631 0.488 0.535 0.649	RMSE = 2.95, 0.84, 0.25, 3.62
11.	*Bambusa stenosstachya*	Li, Lin and Yen (2016)	Taiwan	$AGB = 0.0262 \times (D^2H)^{0.9215}$	20	NA	RMSE = 3.9 MAPE = 11.5%
12.	*Bambusa vulgaris*	Nath, Das and Das (2009)	Barak Valley, India	$log(AGB) = 1.404 + 2.073 \times log((D)$	NA	0.950	NA
13.	*Dendrocalamus barbatus*	Ly et al (2012)	Vietnam	$Bcu =0.44 \times (0.3002 \times D^2 + 0.115 \times D)$	131	0.920	NA
14.	*Dendrocalamus barbatus*	Dung et al, (2012 cited Yuen, Fung and Ziegler, 2017)	Vietnam	$Bcu = 0.113 \times D^{2.102}$	100	0.883	NA
15.	*Dendrocalamus latiflorus*	Liang (1998 cited Yiping et al, 2010)	China	$TB = 0.540 \times D^{1.931}$	NA	0.945	NA
16.	*Guadua angustifolia*	Ricardo et al (2013)	Bolovia	$AGB = 2.6685 \times D^{0.9879}$	24	0.949	NA
17.	*Phyllostachys edulis*	Hao et al (2010 cited Yuen, Fung and Ziegler. 2017)	China	$BGB = - 0.121 \times D^2 + 2.320 \times D - 10$	20	0.560	NA
18.	*Phyllostachys edulis*	Qi et al (2015)	China	$TB = 0.240 \times D^{1.870}$	75	0.930	NA
19.	*Phyllostachys edulis* (Moso bamboo)	Chen et al (2004 cited Kuehl, Lia and Henley, 2013)	China	$AGB = -11.4970 + 3.0465 \times D + 0.1117 \times D^2$	NA	0.837	NA
20.	*Phyllostachys edulis*	Nie (1994 cited Yuen, Fung and Ziegler, 2017)	China	$Bcu = 0.0925 \times D^{2.081}$	NA	0.998	NA

ID	Bamboo species	Author(s) (year)	Location, region	Model	N (number of sampled bamboos)	R^2	Error statistics
21.	*Phyllostachys edulis* (Moso bamboo)	Zhou and Jiang (2004 cited Zhuang et al, 2015)	China	$AGB = 747.787 \times D^{2.771} (0.148 \times A/(0.028 + A))^{5.555} + 3.772$	NA	NA	NA
22.	*Phyllostachys edulis* (Moso bamboo)	Chen (1998 cited Yiping et al, 2010)	China	$TB = 0.2134 \times D^{-0.5805} \times H^{2.3131}$	NA	0.832	NA
23.	*Phyllostachys makinoi* (Makino bamboo)	Yen, Ji and Lee (2010)	Taiwan	$AGB = 0.156 \times D^{2.118}$	20	0.882	RMSE = 0.718
24.	*Phyllostachys makinoi* (Makino bamboo)	Yen, Ji and Lee (2010)	Taiwan	$AGB = 1.112 \times D^{2.695} \times H^{-1.175}$	20	0.898	RMSE = 0.688

The following is an example of model validation of AGB of the *Bambusa stenosstachya* species, developed by Li, Lin and Yen (2016) in Taiwan:

$$AGB = 0.0262 \times (D^2H)^{0.9215}. \qquad (30)$$

The above selected model is applied in the Central Highlands of Vietnam. The local data set collected for validation is 83 destructive bamboo plants in Annex 1. Box 7 introduces the R code to calculate the errors and FI for validation of the model.

Box 7. R code to calculate statistical errors and index of fit to validate the allometric equations

```
# Erase memory
rm(list=ls())

# Clean plot window
dev.off()

# Define the working directory
setwd(“C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data”)

# Import data
t <- read.table(“tAll.txt”, header=T,sep=”\t”,stringsAsFactors = FALSE)

# Install vpackages
library(ggplot2)
library(nlme)
library(cowplot)
library(gridExtra)

# Predicted values and residuals of the model validated
t$prediction = 0.0262 * t$D2H^0.9215
```

```
t$res = t$AGB - t$prediction

# Calculation of statistics
Bias = 100*mean((t$res)/t$AGB)
RMSE = sqrt(mean((t$res)^2))
MAPE = 100*mean(abs(t$res)/t$AGB)
FI = 1 -  sum((t$res)^2)/sum((t$AGB - mean(t$AGB))^2)

# Errors and fit index
Bias
RMSE
MAPE
FI

# Plot of observed vs predicted values
summary(t$AGB)
p1 <- ggplot(t)
p1 <- p1 + geom_point(aes(x=t$prediction, y=AGB), cex = 2)
p1 <- p1 + geom_abline(intercept = 0, slope = 1, col=”black”, cex=1.5)
p1 <- p1 + xlab(“Predicted AGB (kg)”) + ylab(“Observed AGB (kg)”) + theme_bw()
p1 <- p1 + labs(title = “”)
p1 <- p1 + theme(axis.title.y = element_text(size = rel(1.7)))
p1 <- p1 + theme(axis.title.x = element_text(size = rel(1.7)))
p1 <- p1 + theme(plot.title = element_text(size = rel(1.7)))
p1 <- p1 + theme(axis.text.x = element_text(size=15))
p1 <- p1 + theme(axis.text.y = element_text(size=15))
p1 <- p1 + ylim(0,35)
p1 <- p1 + xlim(0,35)
p1

# Plot of weighted residuals vs predicted values
summary(t$res)
p2 <- ggplot(t)
p2 <- p2 + geom_point(aes(x=t$prediction, y=t$res), cex = 2)
p2 <- p2 + geom_line(cex = 1.5, aes(x=t$prediction, y=0))
p2 <- p2 + xlab(“Predicted AGB (kg)”) + ylab(“Residuals (kg)”) + theme_bw()
p2 <- p2 + labs(title = “”)
p2 <- p2 + theme(axis.title.y = element_text(size = rel(1.5)))
p2 <- p2 + theme(axis.title.x = element_text(size = rel(1.5)))
p2 <- p2 + theme(plot.title = element_text(size = rel(1.7)))
p2 <- p2 + theme(axis.text.x = element_text(size=15))
p2 <- p2 + theme(axis.text.y = element_text(size=15))
p2 <- p2 + ylim(-15, 15)
p2 <- p2 + xlim(2.5, 25)
p2

plot_grid(p1, p2, ncol = 2)

# The end
```

Thus, the statistical errors are obtained as Bias = 4.4%, RMSE = 3.7 kg, MAPE = 26.4 % and FI = 0.621. A bias value > 0 and Figure 21 show the model of a slightly underestimated AGB; statistical and FI values demonstrate the model's average rate of reliability.

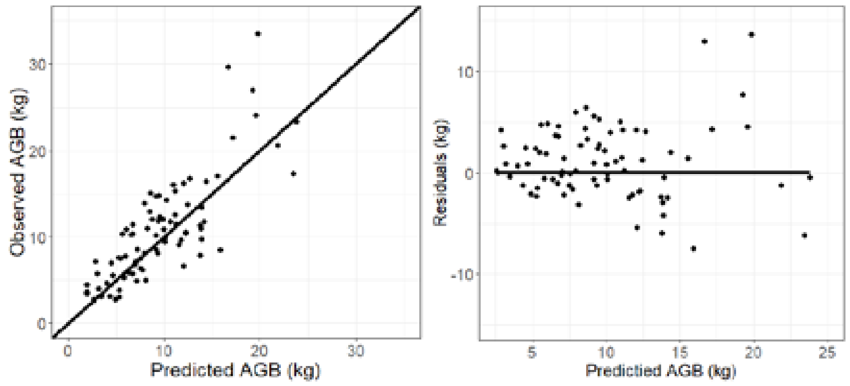


Figure 21. Plot of validated model; observed vs predicted ABG; residuals vs predicted AGB (left to right, respectively).

8. Quality Assurance (QA) and Quality Control (QC) for allometric equation development and validation

To ensure QA and QC, first, organise a short training course titled 'Methodology of carbon estimation for bamboo forest and development and cross-validation of allometric equation'. The suggested curriculum framework is 'Training Short Course Curriculum – Module 1' (see Annex 4).

The biometric models that apply the destructive method often ask for a scientific arrangement to ensure that the accurate data set is collected and correct models are provided. At the stage of collecting data in the field, it is important to use the correct equipment. Therefore, it is necessary to train the staff before proceeding. The data should be recorded by avoiding mistakes in the site; then, after a session, the team leader should cross-check the data to be able to adjust them quickly. The samples gathered to be transferred to the laboratory for biomass carbon analysis should be labelled and encoded sequentially to avoid confusion among the samples. This procedure should be supervised by the team leader in the field.

In the laboratory, the samples that are analysed must be labelled correctly. The analysis results should be entered into the computer and cross-checked. The creation of the data set for modelling should be cross-checked by 2-3 staff members, ensuring that no mistakes have been made during data processing. Modelling should be conducted by trained staff, using specialised statistical software such as R. The result of the model should be referenced, compared and evaluated with real data using a diagram to ensure that no errors have occurred during the setup.

Chapter III. FIELD MEASUREMENT IN BAMBOO FORESTS FOR BIOMASS AND CARBON ESTIMATES

1. Overview of requirements for field data collection for bamboo biomass carbon estimates

The forest inventory is important and is conducted periodically to provide input data for the estimates of forest volume stock and carbon biomass. This work usually requires resources and time; therefore, it should be well organised, effective and reliable. The forest inventory takes place either at national/regional levels or on a small scale (e.g. private forest areas). Field measurement provides two main data groups, which support the estimate of carbon emission/removal, consisting of the changes of forest status areas (Activity Data) and changes of biomass and carbon pools in a unit area and forest status (Emission/Removal Factors).

This manual only introduces the general method of remote sensing (RS) technology to monitor activity data. This guideline focuses on the selection of methods, tools and steps of measurement in the field to provide accurate data for estimating three major carbon pools of the bamboo forest (i.e. in AGB, BGB and litter). The field measurement for assessing forest biomass and carbon requires key resources:

- Human resources: Employees and individuals should be trained to be able to perform the task of field data collection correctly and consistently.
- Equipment and tools should be fully prepared and reliable in gathering data on demand. The list of devices required to work in the field is introduced in Annex 2.
- Time: Organising streamlined time plans will help save resources and reduce costs.

2. Bamboo forest stratification map and measurement of bamboo forest area

2.1. Definition of bamboo forest stratification

- The bamboo forest is an area of forest defined by a country either under the forest definition by the FAO (2010) or by the Kyoto protocol guidelines (UNFCCC 11/CP.7 2001) with a canopy cover of at least 50 per cent of bamboo.
- The mixed bamboo forest is a forest defined by a country either under the forest definition by FAO (2010) or by the Kyoto protocol guidelines (UNFCCC 11/CP.7 2001) with a canopy cover of at least 15 per cent of bamboo.

In addition, there are other types of bamboo forest:

- Bamboo plantation
- Mixed bamboo and other tree plantation

Based on bamboo forest stratification, the data of the forest area, bamboo stock, biomass and carbon are inventoried, monitored and estimated.

2.2. The general mapping of bamboo forest stratification based on RS data

Forest land cover maps are created from high- to medium-resolution RS images. The forest stratification maps are conducted at different administrative levels. These maps are used to monitor forest areas, estimate biomass changes within a stratum and determine the number and location of sample plots (Huy, Sharma and Quang, 2013). The most important types of RS data are (a) aerial photographs, (b) satellite imagery using visible and/or near infrared bands, and (c) satellite or airborne radar imagery. Combinations of different RS data are used for assessing different forest categories (IPCC, 2003). RS has recently become popular in natural resources assessment (Lobovikov et al, 2007) because it is a fast, reliable, accurate and inexpensive method of stratifying, evaluating and mapping the natural resources.

However, it might be difficult to apply RS analysis to bamboo forests compared with other forest types. Sympodial bamboo makes it more difficult to determine the imagery, because it grows in smaller clusters. The bamboo forest areas can be confused with those of other crops. As well as this, bamboo forest areas are often scattered across the forest and other agricultural lands and thus require greater field validation (Lobovikov et al, 2007).

The process of analysing RS for establishing bamboo forest stratification map is as follows (Figure 22, after Petrova et al, 2010):

1. Selection and combination of appropriate RS data

There are various types of RS data, such as aerial photographs, airborne radar imagery and satellite imagery, whereby optical RS imagery types such as Landsat (MSS, TM and ETM+), SPOT, ASTER, DMC, Radar data and LiDar data are currently available and appropriate for developing forest stratification maps on national and sub‑national scales (Petrova et al, 2010). For the image classification of bamboo forests, medium-resolution images (e.g. Landsat with 30 m resolution) or high-resolution images (e.g. IKONOS, SPOT, Rada data and Lidar) are suitable for mapping. It is important to apply time series imagery processing to mapping bamboo forests, as this method can help distinguish bamboo from other vegetation.

2. *Image pre-processing*

Radiometric, geometric correction and shadow and cloud removal should be done before using image for forest stratification.

3. *Image enhancement*

Image enhancement algorithms may be applied to improve the imagery for visual or automated analysis.

4. *Image forest stratification*

There are many methods for classifying satellite images and creating forest land cover maps. Common forest stratification procedures can be divided into three major types: supervised, unsupervised and other image classification techniques. Owing to the characteristics of located bamboos, the image classification for bamboo forest stratification requires sufficient ground-truth training data with exact GPS coordinates (Lobovikov et al, 2007). For the classification of bamboo forests using imagery, a collection of data sets should be created, which includes ground-truth data with precise GPS coordinates and/or high-resolution images that can be extracted. The collected data sets are randomly split into two parts: about 70-80 per cent for image stratification analysis and 20-30 per cent for accuracy assessment.

5. *Accuracy assessment*

There are two main types of errors in stratification maps, derived from RS imagery: positioning and thematic errors. Positioning error refers to the mistakes in the actual placement of the class or features on the map; thematic error refers to the wrong stratification classes on the map that are supposed to be realistic. There are different ways to calculate the statistical accuracy of the forest land cover and stratification map. The most common accuracy statistics are overall accuracy, producer's accuracy and user's accuracy. Using 20-30 per cent randomly split ground-truth data validates the accuracy of the classification image.

The accuracy of bamboo forest stratification is recommended to be over 80 per cent. In cases where the accuracy of the bamboo forest category cannot reach the required reliability, change to a different method for image stratification may be considered, or new training data may be collected to incorporate the pixels value variability for bamboo forest classification.

To be consistent with 2006 IPCC, please refer to FAO's free tool Collect Earth (www.openforis.org/tools/collect-earth.html) and GFOI MGD2.0 (www.reddcompass.org/download-the-mgd).

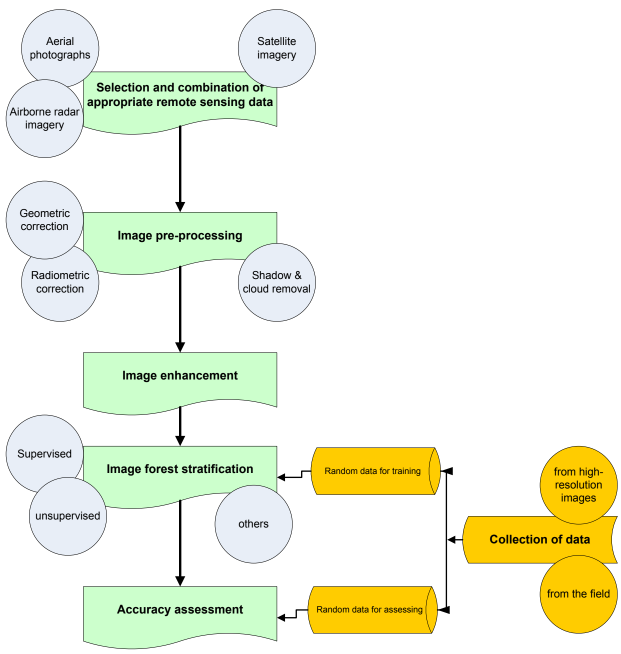


Figure 22. Process of forest stratification using RS imagery.

Thus, the analysis of image stratification creates a raster map that consists of different forest categories, of which the bamboo forest can be one or more forest types, such as bamboo forest, mixed bamboo forest, bamboo plantation, and mixed bamboo and other tree plantations. Figure 23 shows an example of a map of bamboo forest stratification, created using satellite imagery, which consists of a bamboo forest and a mixed bamboo forest in Lam Dong Province of Vietnam.

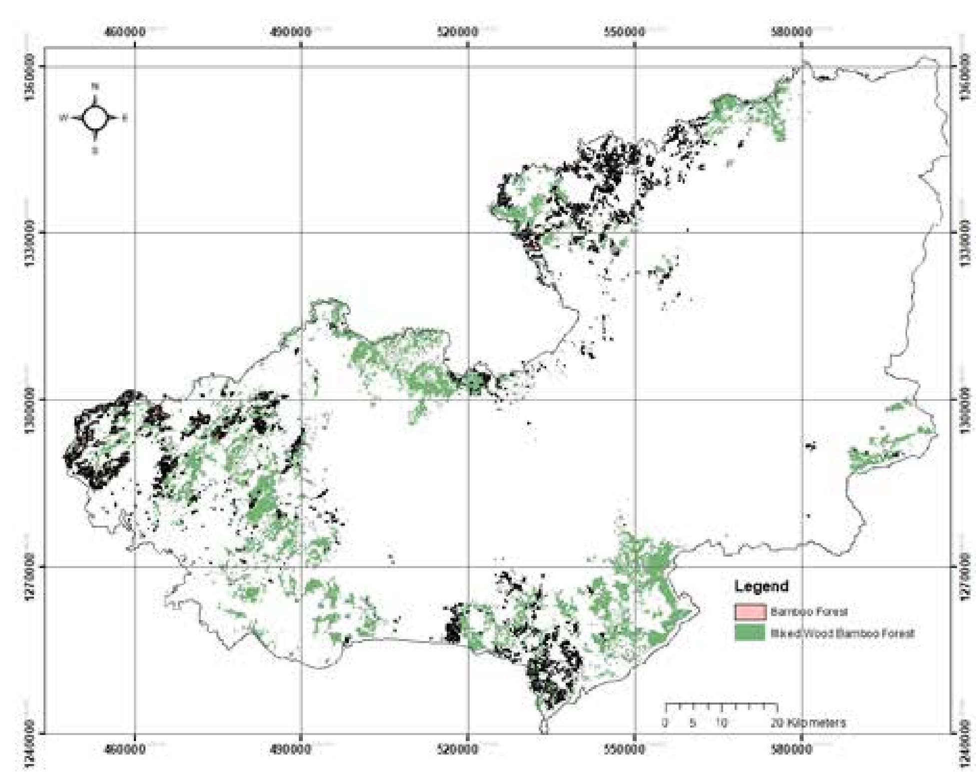


Figure 23. Map of bamboo forest stratification, created from satellite images in Lam Dong Province (Source: VNForest, 2017).

2.3. Using a geographical information system (GIS) to monitor and manage bamboo forest areas

A GIS is generally integrated with RS for storing and analysing data and producing maps of forest stratification and its associated statistics. This integration can significantly support the monitoring and analysis of bamboo cover changes. The RS image creates a forest classification map, combined with data management in GIS (e.g. intersection) (Figure 24) of administrative map layers; the forest owner layers create a new map layer that contains diverse fields of data such as the administrative management units, forest owners and forest information (e.g. forest classes, types, forest status, area, volume, biomass and carbon). From here, it is possible to export different types of maps and aggregate data, depending on the purpose of use. Figure 25 illustrates an example of a map of bamboo forest according to the administrative management unit and Table 22 shows its attributes.

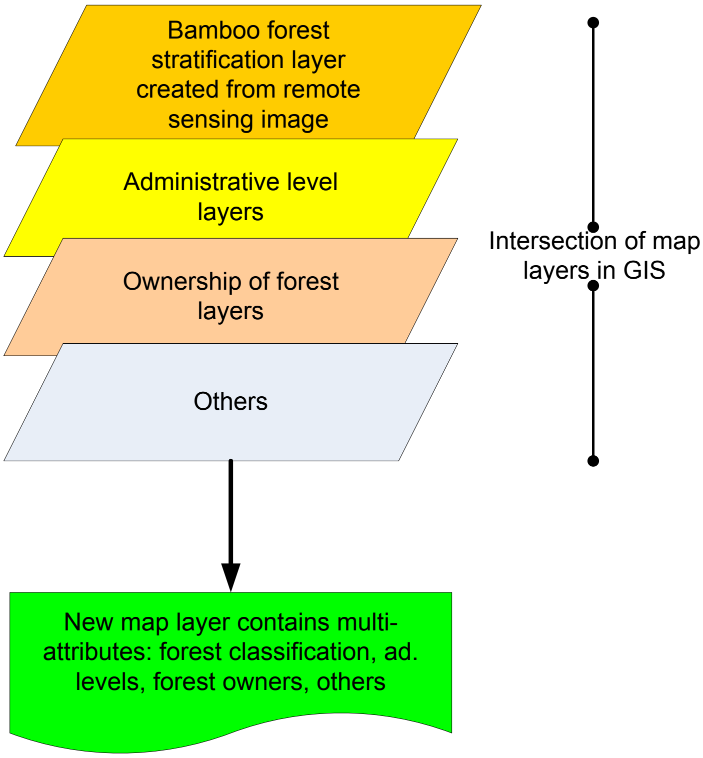


Figure 24. Integration between RS and GIS to create multi-maps and an attribute data set.

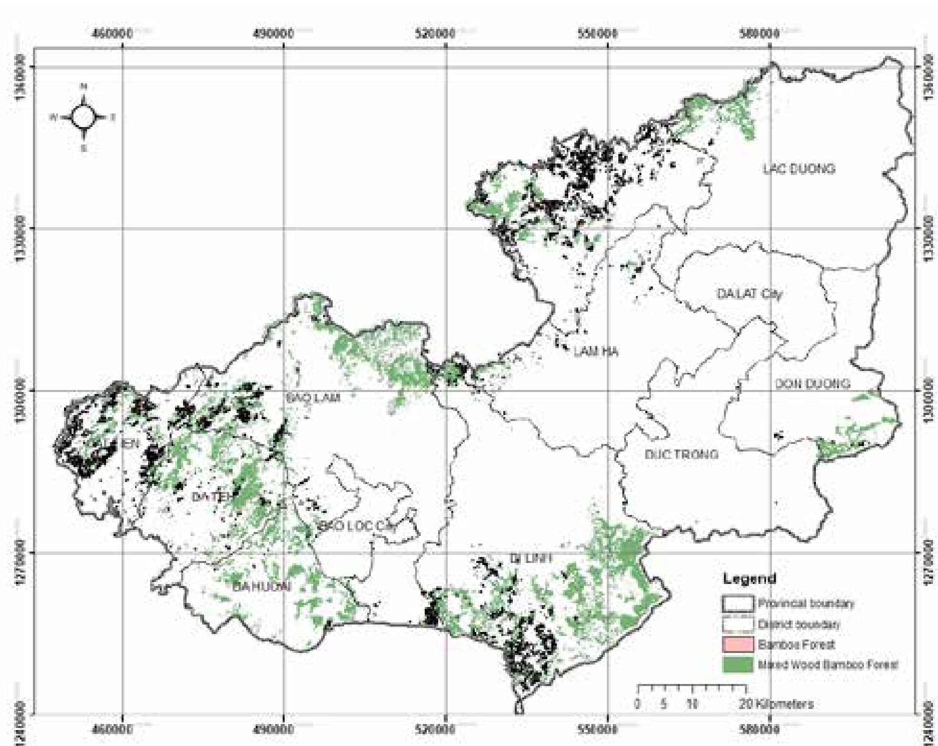


Figure 25. Map of bamboo forests, distinguished among administrative levels of province and district/city created using a GIS.

Table 22. Attribute table of an intersection map layer exported from GIS

Table

Bamboo_Forest_Lam_Dong_Province_Vietnam

FID	Shape *	TT	id	matinh	mahuyen	maxa	xa	tk	khoanh	lo	thuad	tobando	ddanh	dtich	nggocr	ldlr
0	Polygon ZM	185	0	68	679	25006	Tân Thượng	618A	3	2	0	2	Thôn 3	1.18	1	HG1
1	Polygon ZM	191	0	68	679	25006	Tân Thượng	618A	8	1	0	2	Thôn 3	1.12	1	HG1
2	Polygon ZM	196	0	68	679	25006	Tân Thượng	618B	3	2	0	2	Thôn 3	6.82	1	HG1
3	Polygon ZM	263	0	68	679	25021	Tam Bố	678	2	19	0	6	Tam Bố	0.13	1	HG1
4	Polygon ZM	269	0	68	679	25021	Tam Bố	645	14	4	0	2	Tam Bố	0.61	1	HG1
5	Polygon ZM	271	0	68	679	25021	Tam Bố	678	1	22	0	6	Tam Bố	6.85	1	HG1
6	Polygon ZM	274	0	68	679	25021	Tam Bố	678	2	26	79	6	Thôn 5	10.64	1	HG1
7	Polygon ZM	275	0	68	679	25021	Tam Bố	678	2	25	65	6	Thôn 5	11.73	1	HG1
8	Polygon ZM	276	0	68	679	25021	Tam Bố	678	2	22	0	6	Thôn 5	10.25	1	HG1
9	Polygon ZM	277	0	68	679	25021	Tam Bố	678	2	21	0	6	Thôn 5	1.33	1	HG1
10	Polygon ZM	278	0	68	679	25021	Tam Bố	679	2	27	0	6	Tam Bố	1	1	HG1
11	Polygon ZM	279	0	68	679	25021	Tam Bố	678	2	24	0	6	Thôn 5	0.65	1	HG1
12	Polygon ZM	283	0	68	679	25021	Tam Bố	678	3	20	84	6	Thôn 5	18.24	1	HG1
13	Polygon ZM	285	0	68	679	25021	Tam Bố	678	3	16	0	6	Thôn 5	12.26	1	HG1
14	Polygon ZM	286	0	68	679	25021	Tam Bố	678	3	24	0	6	Tam Bố	0.69	1	HG1
15	Polygon ZM	294	0	68	679	25021	Tam Bố	678	3	22	91	6	Thôn 3	18.86	1	HG1
16	Polygon ZM	326	0	68	679	25048	Sơn Điền	709B	7	22	0	3	Hà Giang	0.44	1	LOO
17	Polygon ZM	327	0	68	679	25048	Sơn Điền	709B	8	47	0	3	Hà Giang	0.47	1	HG1
18	Polygon ZM	328	0	68	679	25048	Sơn Điền	709B	8	45	0	3	Hà Giang	0.49	1	LOO
19	Polygon ZM	337	0	68	679	25048	Sơn Điền	709B	9	41	0	3	Hà Giang	0.37	1	HG1
20	Polygon ZM	345	0	68	679	25048	Sơn Điền	710	6	14	0	2	Thôn Bó Nơm	0.43	1	LOO
21	Polygon ZM	346	0	68	679	25048	Sơn Điền	710	6	13	0	2	Thôn Ka Liêng	0.25	1	LOO
22	Polygon ZM	347	0	68	679	25048	Sơn Điền	715	1	11	0	2	Thôn Bó Nơm	0.41	1	HG1
23	Polygon ZM	348	0	68	679	25048	Sơn Điền	715	1	12	0	2	Thôn Bó Nơm	0.49	1	LOO
24	Polygon ZM	349	0	68	679	25048	Sơn Điền	715	1	14	0	2	Thôn Bó Nơm	0.25	1	LOO
25	Polygon ZM	350	0	68	679	25048	Sơn Điền	715	4	13	0	2	Thôn Bó Nơm	0.24	1	LOO
26	Polygon ZM	364	0	68	679	25048	Sơn Điền	716	8	24	0	4	Thôn Ka Liêng	0.21	1	HG1

(0 out of 9187 Selected)

Bamboo_Forest_Lam_Dong_Province_Vietnam

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In the GIS, the attribute table of the intersection map layer can be exported to Excel sheets and from there, the Pivot table tool is helpful in making different reports (Table 23) for forest management.

Table 23. A report on bamboo forest area under administrative levels made using an Excel Pivot table

Code district	Mixed wood bamboo forest (ha)	Bamboo forest (ha)	Total (ha)
673	24.7		24.7
674	6595.9	5159.9	11,755.7
675	5235.7	98.3	5334.0
676	1348.4	284.6	1633.0
677	3149.1	73.5	3222.6
678		3.4	3.4
679	26,011.0	2992.9	29,003.9
680	18,908.1	1946.7	20,854.9
681	9123.4	51.9	9175.3
682	12,552.1	536.9	13,089.0
683	4769.3	5148.0	9917.2
Total (ha)	87,717.7	16,296.1	104,013.7

3. Sampling design

IPCC (2003, p. 5.22) offers the following definition: 'Sampling design determines how the sampling units (the sites or plots) are selected from the population and thus what statistical estimation procedures should be applied to make inferences from the sample'. Additionally, Lackmann (2011, p. 3) provides this definition: 'The sampling design should aim for a good compromise between accuracy and costs of the estimates'. The type of sample plots used in forest inventories includes fixed area plots, which can be nested or clustered, variable radius or point sampling plots (e.g. prism or relascope plots) or transects (IPCC, 2003). Accuracy, at a reasonable cost, is expected to target 10 per cent of the actual value of the mean at a 95 per cent confidence level (Petrova et al, 2010). The sampling design involves selecting the plot shape, plot size, sampling size, plot layout and permanent vs temporary plot, etc.; these are introduced in the following sections.

3.1. Plot shape

3.1.1. Different sample plot shapes for bamboo forest measurement

Forest inventory for bamboo forests are used for selecting one of the sample shapes such as a circle, square or rectangle for running bamboo, clumping bamboo with no dense culms or clump-based sampling. A circular plot is applied to bamboo species in Vietnam with a radius of R = 5.64 m and an area of 100 m^2 (Dung, Anh and Vinh, 2018). Many researchers use square and rectangle plot areas depending on the density of the bamboo species. For example, Yuen, Fung and Ziegler (2017), Qi et al (2015) and Tran (2010) used a square plot for *Phy. edulis* species of 20 × 20 m, or Kaushal et al (2018) applied a 25 × 25 m square or a rectangle of 5 × 40 m or 20 × 25 m, while some other researchers chose a 10 × 10 m square for Mosco bamboo, *Bambusa vulgaris* (e.g. Zhuang et al, 2015; Xu, Ji and Zhuang, 2018).

As for clumping bamboo with very dense culms, if it is not possible to form a circular or square/rectangle plot, clump-based sampling may be useful (Vnforest, 2011). This type of sampling is used to determine the number of bamboo clumps per unit area (e.g. ha) – based on the averaged distance among bamboo clumps – measure the D and H of several average culms and count the number of bamboo culms per clump (Figure 38).

3.1.2. Conditions and recommendations for selecting appropriate plot shapes

Clump-based sampling should only be applicable when it is impossible to form circular or rectangular plots through dense culms of clumping bamboo type. Clump sampling does not measure each culm; but rather, it measures the average bamboo culm in a clump, and biomass is calculated from the averaged plant and the number of culms per clump, hence giving a low reliability.

Square or rectangular plots are particularly vulnerable to errors in the plot area; this is because of the larger boundary around the plot than there is for a circle plot with the same area and a difficult form, particularly when the plot is on the slope. In addition, it is difficult to make a correct angle of the plot corners, especially on the sloping land; therefore, a wrong angle would significantly change the area of the plot and bias the estimates (Lackmann, 2011). However, square or rectangular plots are useful on flat lands with scattered grown bamboo and with no dense culms.

Circular plots are more efficient because the actual perimeter of the plot is smaller than the square/rectangular plots in relation to the area and, thus, the number of the bamboo culms on the edge is limited and need not be marked (Lackmann, 2011; Petrova et al, 2010). Besides, circular plots are easy to set up on steep lands with an extra radius which can extend to adjustable areas on the slope.

Distance measuring equipment (DME) or Laser measuring instrument such as LaserAce is recommended for circular plots. However, if neither DME or LaserAce is available, the circular plot can be laid out using ropes with knots and stakes (Huy, Sharma and Quang, 2013). Therefore, while circular plots may be easier to establish than square/rectangular plots, they also cause a problem when clumping bamboo is very dense with culms because in such cases, it is difficult to measure the radius of the circular plot using either DME/ LaserAce or ropes with knots and stakes. Table 24 shows some suggestions for selecting the plot shape for bamboo measurement.

Table 24. Comparison of the advantages and disadvantages of appropriate plot shapes for bamboo measurement

Plot shape	Advantage	Disadvantage	Remark
Circular plot	- The perimeter of the plot is smaller than the square/ rectangular plots. - It is easy to set up on the sloping land without any angle. - For running bamboo or clumping bamboo with no dense culms, it can achieve the correct radius.	- If the clumping bamboo is very dense with culms, it is difficult to measure the radius of the circular plot.	In many cases, the circular plot is more efficient.
Square/ rectangular plots	- On a flat land, it can achieve the correct angles. - For running bamboo or clumping bamboo with no dense culms, it can achieve the correct boundary.	- On a sloping land, it is difficult to make a correct angle of the plot corners. - The perimeter of the plot is larger than the circular plot. - If clumping bamboo is very dense with culms, it is difficult to form the plot.	The square/rectangular plots are only suitable for flat lands and running bamboo.
Clump-based sampling	- For clumping bamboo with very dense culms, it is easy to measure correctly only distances among clump. - On a sloping land, there is no angle.	- For running bamboo with no dense culms.	The clump sampling should only be applied to clumping bamboo with very dense culms and where it is hard to establish either the circular or the rectangular plot.

In fact, bamboos grow with timber trees; therefore, examination of a bamboo forest is usually carried out at the same time as a timber forest inventory. In this case, the nested plot should be used. Therein, the plot is split into subplots where larger timber trees are measured in larger subplots and a proper subplot is used to measure the bamboos. Figures 26 and 27 demonstrate two types of nested plots in the shapes of a circle and a square, which are used to measure timber trees and bamboos in the forest inventory.

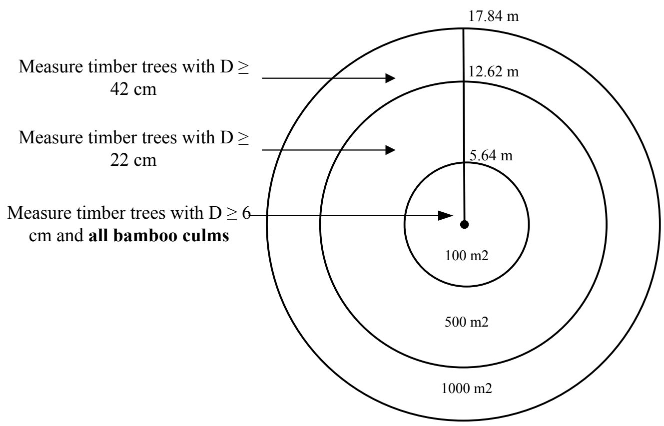


Figure 26. Nested circular plot, consisting of three concentric subplots to measure different size timber trees and bamboos (Huy, Sharma and Quang, 2013).

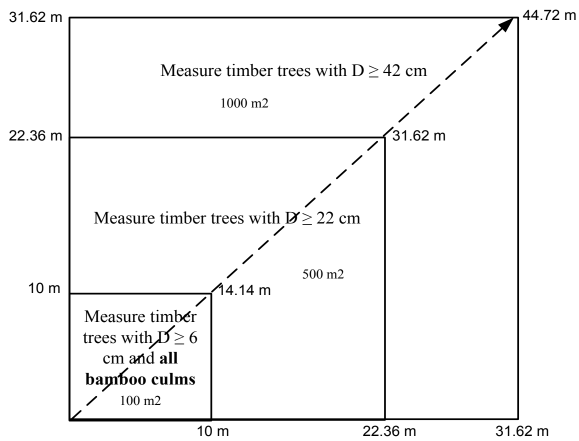


Figure 27. Nested square plot, consisting of three subplots to measure different size timber trees and bamboos.

3.2. Plot size

According to the bamboo forest inventory and research, plot sizes vary based on bamboo species, depending on their density of culms, clumps and running or clumping bamboo types. The most commonly used sizes are from 100 m^2 to 400 m^2. The 100 m^2 circular or square plot is used for *Phyllostachys pubescens, Bambusa vulgaris* and *Phyllostachys makinoi* (Dung, Anh and Vinh, 2018; Zhuang et al, 2015; Xu, Ji and Zhuang, 2018; Yen, Ji and Lee, 2010; Zhang et al, 2014), while the 400 m^2 square plot is used for *Phy. edulis* and *B. nutans* (Yuen, Fung and Ziegler, 2017; Qi et al, 2015; Tran, 2010).

The choice of appropriate sample plot size should consider the following principles (Lackmann, 2011):

- The larger the plot size, the more time-consuming and costly the measurement, while reducing the variation among the plots decreases the required number of plots by the same precision.

- The plot size depends on the density of plants. The size should be large enough to ensure the reliability of the average value of the plants measured in the plot.

The size of the plots is a trade-off between measurement accuracy, precision, time and cost (Petrova et al, 2010). Therefore, it is necessary to balance the above-mentioned principles; the size of the sample plot, which requires a minimum area allowing the measured value (e.g. diameter) distribution near the normal distribution; and the average plant, representing the forest stand; thus the plot size should have a minimum of 50 culms. At the same time, the size should be large enough to reduce the number of the required plots by the same precision; however, it should not be too time-consuming and expensive. Table 25 offers several recommendations for selecting the appropriate plot size for the various densities of different bamboo species.

Table 25. Selection of appropriate sample plot size based on the number of bamboo culms

ID	Plot size	Running bamboos		Clumping bamboos	
		Culms per ha	Culms per plot	Clump per ha	Clump per plot
1	100 m^2	6000-over 12,000	60-120	150-200	1.5-2
2	200 m^2	3000-6000	60-120	50-150	1-3
3	400 m^2	< 3000	60-120	20-50	1-2

3.3. Sampling size (number of sample plots) and precision

According to IPCC (2003), the number of sample plots for estimating biomass and forest carbon must be determined in such a way that the error in estimation is below 10 per cent of the mean at each stratum at a 95 per cent confidence level. If the error is greater than 10 per cent, further investigation may be needed. A preliminary inventory needs to be completed to estimate the expected variance of the biomass carbon stock in the living plants in each forest stratum and to estimate the required number of plots. Preliminary inventory must be carried out in 10 to 15 (preferably 30) randomly selected plots in each forest stratum within the owner's boundary and/or ecological zone (Subedi et al, 2010; Huy, Sharma and Quang, 2013).

At the basic level, the number of plots required should be defined by the following formula (Pearson, Brown and Birdsey, 2007; Huy, 2017b):

$$n = \left(\frac{t \times S}{E}\right)^2 = \left(\frac{t \times CV\%}{E\%}\right)^2 \quad (31)$$

where the forest area is composed of strata such as bamboo forest, mixed wood bamboo forest or bamboo plantation, a complex equation should be used as follows (Lackmann, 2011; Huy, 2017b):

$$n = \frac{t^2 \times CV\%^2}{E\%^2 + \frac{t^2 \times CV\%^2}{N}} \quad (32)$$

$$n_i = n \times \frac{N_i}{N} \quad (33)$$

where *n* is the total number of the required sample plots within the forest area; and n_i is the required number of the sample plots for stratum i; *t* is the sample statistic from the *t*-distribution at 95% confidence level (*t* is usually set at 2); *S* is standard deviation; *E%* is the allowable error in per cent (e.g 10%); *E* is the desired level of precision = E% × $\bar{X}$ with $\bar{X}$ is the mean biomass/carbon of the plot; CV%

is the coefficient of variation in per cent = (S/ $\overline{X}$) × 100. *N* is the maximum possible number of sample plots in the forest area; *A* is the total area of the forest (ha); *AP* is the sample plot size (ha); *Ni* is the maximum possible number of sample plots in stratum i and *Ai* is the area of stratum i (ha),

$$N = \frac{A}{AP} \tag{34}$$

$$N_i = \frac{A_i}{AP} \tag{35}$$

The example in Box 8 demonstrates the calculation of the number of the sample plots for each stratum of bamboo forest and mixed wood bamboo forest.

Box 8. Calculation of the required number of sample plots for bamboo forest and mixed wood bamboo forest in Loc Bao Commune, Bao Lam District and Lam Dong Province of Vietnam

The input information of the bamboo forest in Loc Bao Commune is as follows:
$A = 3914$ ha; $A_{bamboo} = 63$ ha; $A_{mixed} = 3851$ ha; AP = 0.01 ha

$$N = \frac{A}{AP} = 3914 / 0.01 = 391{,}400$$

$$N_i = \frac{A_i}{AP}$$

The maximum possible number of sample plots in bamboo forest stratum:
$N_{bamboo} = 63/ 0.01 = 6{,}300$
The maximum possible number of sample plots in mixed wood bamboo forest stratum:
$N_{mixed} = 3851 / 0.01 = 385{,}100$

Collect 17 random sample plots of 0.01 ha and calculate the AGB_{bamboo} for each plot using an allometric equations for *Bambusa procera* species: $AGB = Bcu + Bbr + Ble$. Then, use the descriptive statistics tool in Excel (i.e. Data/Data Analysis/Descriptive Statistics) and attain the value of mean and standard deviation (S) and then calculate CV% presented in the sheet below.

Plot ID	AGB per plot 100 m2 in kg	Total AGB per ha in tonne
L1	2044.5	204.4
L10	520.0	52.0
L11	242.7	24.3
L12	692.9	69.3
L13	340.1	34.0
L14	832.7	83.3
L15	706.6	70.7
L16	385.4	38.5
L17	655.8	65.6
L2	972.7	97.3
L3	251.5	25.2
L4	441.4	44.1
L5	656.9	65.7
L6	831.0	83.1
L7	693.0	69.3
L8	764.9	76.5
L9	550.2	55.0

Descriptive statistics	
Mean	68.131
Standard error	9.925
Median	65.691
Standard deviation	40.922
Sample variance	1674.630
Minimum	24.271
Maximum	204.446
Sum	1158.229
Count	17
Conf. level 95%	21.040
CV%	60.1%

Mean AGB = 68.1 tonne/ha; Standard deviation (S) = 40.9 tonne/ha;
CV% = (S/Mean) × 100 = (40.9/68.1) × 100 = 60.1%

The calculation of the total number of the required plots with E% is 10% and t = 2:

$$n = \frac{t^2 \times CV\%^2}{E\%^2 + \frac{t^2 \times CV\%^2}{N}} = \frac{2^2 \times 60.1\%^2}{10\%^2 + \frac{2^2 \times 60.1\%^2}{391,400}} = 144 \text{ plots}$$

$$n_i = n \times \frac{N_i}{N}$$

The number of the required plots for each stratum of bamboo forests:

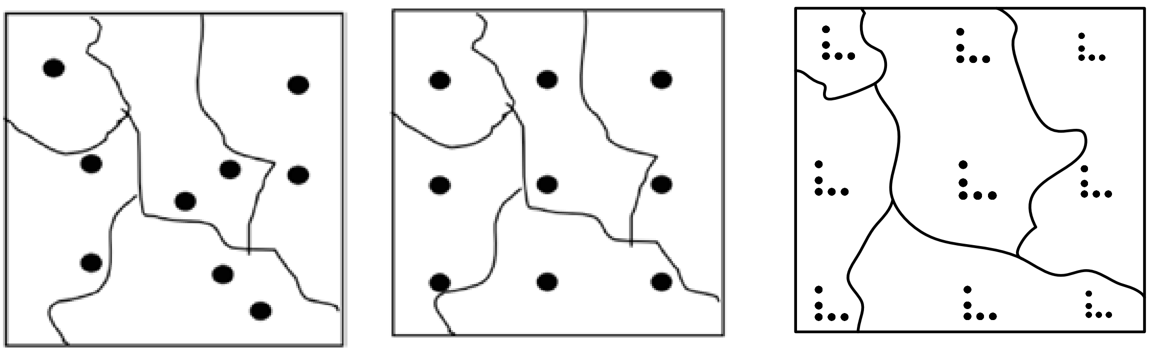
n_{bamboo} = 144 * 6,300 / 391,400 = 2 plots

n_{mixed} = 144 * 385,100 / 391,400 = 142 plots

3.4. Plot layout

3.4.1. Different layouts of plots

In forest inventory, there are some main, applicable plot layouts, such as random, systematic and cluster samplings (Figure 28).



Simple random layout of plots | Systematic layout of plots | Cluster of plots (within a systematic sampling, sample plots are organised into clusters)

Figure 28. Plot layout types for forest inventory.

i) Random layout of plots

To avoid the subjective choice of plot locations, the sample plot system should be located randomly on a forest stratification map (Lackmann, 2011). The random sample layout ensures its suitability for the application of mathematical statistics to calculate the average values, variance, errors and distributions. Random sample plots can be performed with a random function in the GIS, which is introduced in the next section of this manual.

ii) Systematic layout of plots

It is a systematic (grid) sampling design with a random start. The grid intersection covers the forest area of interest. The grid size (spacing) depends on the sampling size (number of required sample plots) (ITTO, 2013).

The formula for the square grid spacing (S, m) is as follows:

$$S = \sqrt{\frac{A}{n}} \quad (36)$$

where *A* is the total area of inventory in m^2, and *n* is the total number of required sample plots.

For example, in Loc Bao Commune, A = 3914 ha = 3914 × 10^4 m^2, n = 144 plot, then the spacing among plots is

$$S = \sqrt{\frac{A}{n}} = \sqrt{\frac{3914 \times 10^4}{144}} \sim 520\ m \quad (37)$$

iii) Cluster layout of plots

Sample plots are organised into clusters (i.e. groups of sample plots located near each other within a systematic layout sampling). However, it cannot be very efficient if the sampling units in one cluster are correlated. Therefore, distances between the units in one cluster should be large enough to avoid major between-plot correlations (at least 250-300 m, depending on the size of stratum) (Lackmann, 2011).

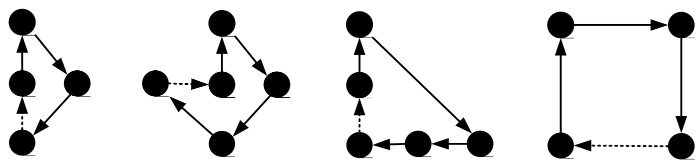


Figure 29. Walking distances for different cluster types with different travel routes; the dotted lines are the return distances (Yim et al, 2015).

The effectiveness of the cluster plots depends on the number and arrangement of the sampling units in one cluster; the cluster size affects accuracy and the total working time (Figure 29). For clusters of four subplots, a triangular cluster gives the best results for both statistical analysis and cost (Yim et al, 2015).

iv) Typical plots

If the forest investigation area is small (< about 20 ha) with discrete distribution, then the application of random, systematic or cluster layouts is not feasible and necessary. Therefore, a typical sampling is applicable. In each of the forest blocks, select 2-3 points for the plots, which reflect average density, bamboo size, etc.

3.4.2. Conditions and recommendations for selecting suitable plot layouts

Random and systematic sampling strategies prevent the subjective choice of plot locations and allow the application of statistics for data analysis, whereby random sampling is most effective and significant in processing data statistics. Thus, most of the forest surveys adopted are from one of these methods. Previously, when there were no GIS and GPS technologies, the systematic layout of plots was preferred because it was easy to locate the plots in the field, based on the compass and tape rule. However, the deviation was also very large on the complex terrain and dense forest vegetation. Today, with the developed technology, it is easy to organise the random sample system on the map in a GIS programme and upload the waypoints to GPS to determine the exact position of the random plots in the field (see the next section of the manual for further details). Therefore, bamboo inventory should select random sampling as a preferred option.

Clusters of subplots are suitable only for large areas of forest monitoring, where travel time between the sample points is a crucial cost factor (Yim et al, 2015). Clusters are extremely cost-effective; they reduce travel distances between the sample plots and thus more units can be measured to increase the accuracy of the estimates (Lackmann, 2011; Pearson, Brown and Birdsey, 2007). The cluster layout cannot be applied when the forest status changes continuously and is intermingled with each stratum area if that is small (e.g. small bamboo areas in the forest wood strata).

Typical plot location is only applicable to small bamboo forest stratum areas or individual blocks of bamboo plantation.

3.5. Permanent vs temporary plots

Sample plot systems can be designed differently to assess changes in terms of (a) permanent sampling plots, (b) temporary sampling plots and (c) sampling with partial replacement (Lackmann, 2011).

i) Permanent sampling plots

The plot system is set up and coordinated in the field for long-term monitoring and inventories, which is repeated multiple times and for a long time. This type of sampling design is used to monitor the gain and loss of bamboo volume as well as the biomass and carbon in carbon pools, which provide the precise amount of forest carbon emissions or removals. For circular plots, at the plot centre, hammer a section of a metal bar into the ground. For square/rectangular plots, mark each of the corners with a metal bar, including the corners for each subplot of the nested plots (Petrova et al, 2010).

ii) Temporary sampling plots

The plot system is set up for one-off measurement only. Because there is no repetition, the measurement data are aimed at providing the values of the volume and biomass at the time of investigation. When plots are temporary, they need only be marked sufficiently to facilitate the one-off measurement. For circular plots, use a stake and mark the centre point of the plot; for square/rectangular plots, mark the GPS waypoints and all the corners of the subplots with stakes (Petrova et al, 2010).

iii) Conditions and recommendations

Apply the permanent plots when you want to study the forest dynamics and change the carbon pools over time. However, in carbon forest projects, if land managers know the permanent plot locations, they will avoid activities in these plots. In that case, the permanent plots are no longer representative of the forest status changes and lead to biased results (Petrova et al, 2010). The temporary plots are more flexible than the permanent ones, helping to reduce the cost of management and preserving the plots; however, we cannot know the forest dynamics, forest carbon emissions or absorption, which are usually used in annual forest inventory and monitoring.

3.6. Design random sample plots in GIS map and upload to GPS

3.6.1. Design of random sample plots in the GIS map

Sample plot systems should be randomly assigned to a map with coordinates of every plot. These will form the basis for determining the positions in the field, where forest plants and biomass are measured. Once the number of the required plots is determined, the random plot locations can be determined for each stratum using 'Create random point' tool in ArcGIS, and then the map of random sample plots is produced (Huy, Sharma and Quang, 2013) (Figure 30).

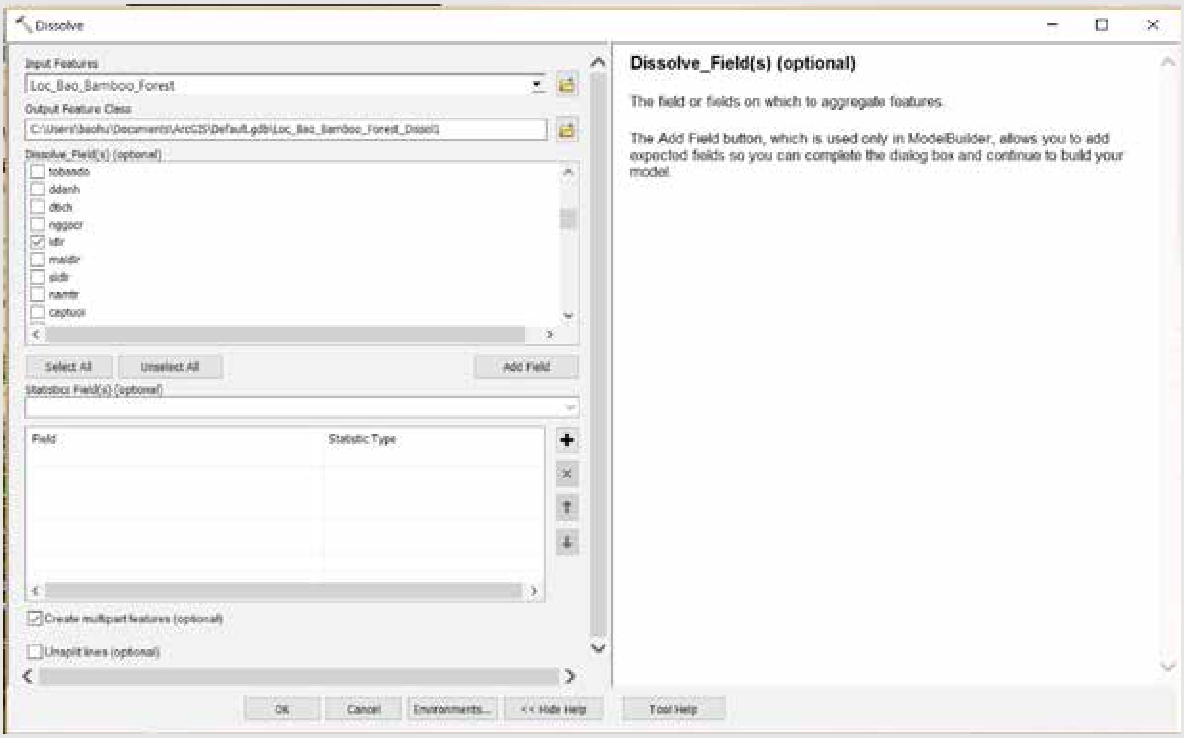
Box 9 introduces a procedure to design random plots in GIS map using the ArcGIS programme.

Box 9. A procedure to design random plots in GIS forest stratification map using the ArcGIS programme

Step 1: Dissolve spatially discrete forest blocks by forest status.

The purpose of this step is to create homogeneous strata of forests. Spatially discrete forest blocks with similar strata are combined into one stratum. Use the following two steps in ArcGIS:

- Select the data layer that contains polygons of forest status blocks
- Use Dissolve to combine all the polygons that have the same status:
  - Select the Dissolve tool
  - In the dialogue box shown below, select the data layer that contains the forest status in Input Feature. Specify the output file in Output Feature Class. Select the forest status field under Dissolve Field. Click OK.



Step 2: Enter the number of required sample plots for each forest stratum in the attribute table of the forest stratification map.

A field 'Number_of_Plots' (of type – numeric) is created in the attribute table of the GIS map layer, containing the dissolved stratum. Then enter into this field the number of required sample plots for each stratum determined.

Table

Loc_Bao_Bamboo_Forest_Dissol

FID *	Shape *	Forest Type	Shape_Length	Shape_Area	Area	Number_of_Plots
1	Polygon ZM	Mixed	369268.34346	38508108.436217	3851	142
2	Polygon ZM	Bamboo	20918.925252	625799.854714	63	2

1 (0 out of 2 Selected)

Loc_Bao_Bamboo_Forest_Dissol

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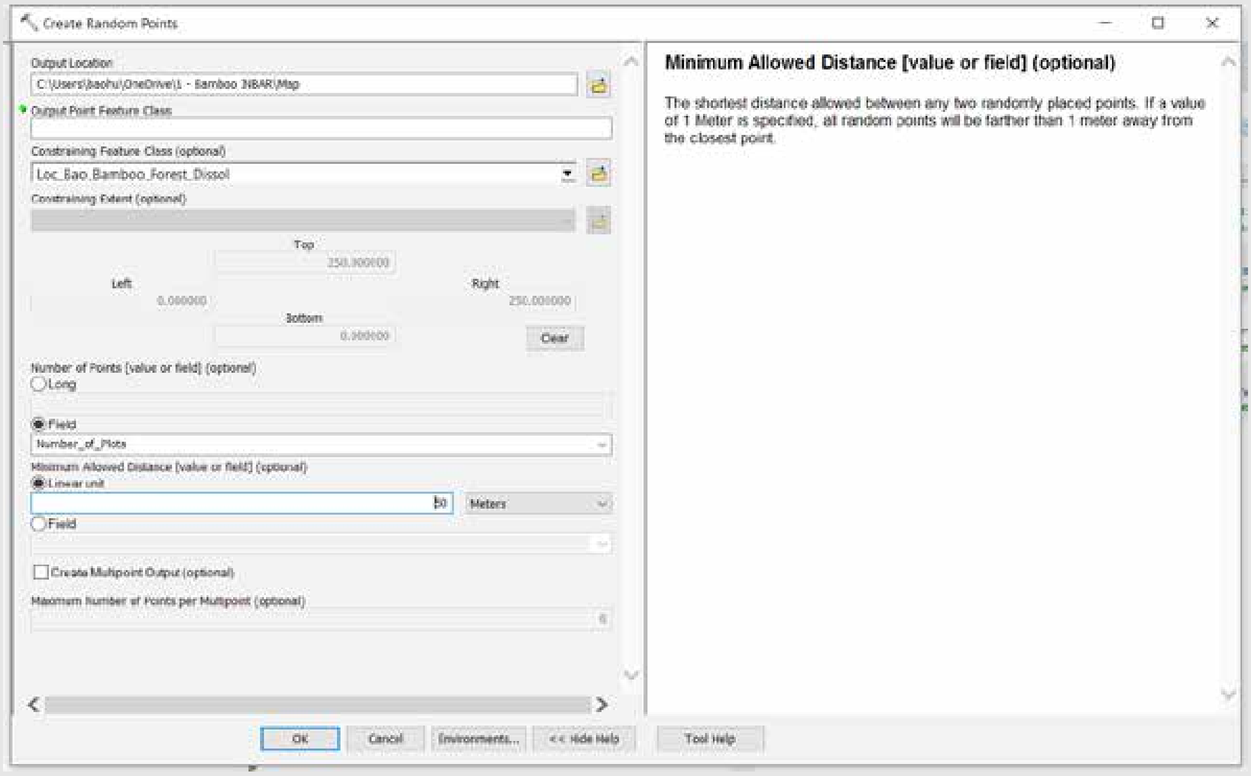
Step 3: A network of random sample plots are created and overlaid on the dissolved forest stratum (polygons):

In ArcGIS tool, select Create Random Points, as shown below:

- Select Output location

- Select map layer of dissolved stratum
- Number of Points: Select Field and then select field ‘Number_of_Plots’
- Enter an appropriate value for Minimum Allowed Distance. This is the smallest distance allowed between two randomly placed plots.
- Click OK



The result is a network of random plots on a forest stratification map (Figure 30).

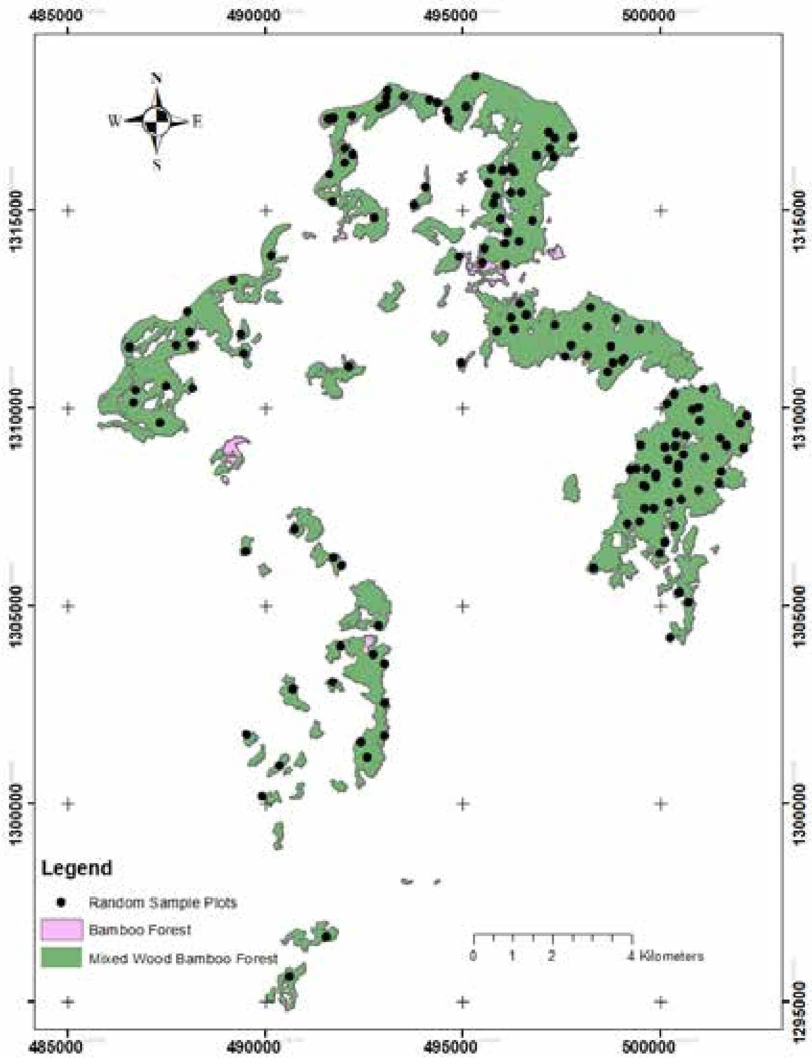


Figure 30. Map of random sample plots in bamboo forests in Loc Bao Commune, Bao Lam District, Lam Dong Province, Vietnam.

3.6.2. Upload the coordinates of the random sample plots to the GPS

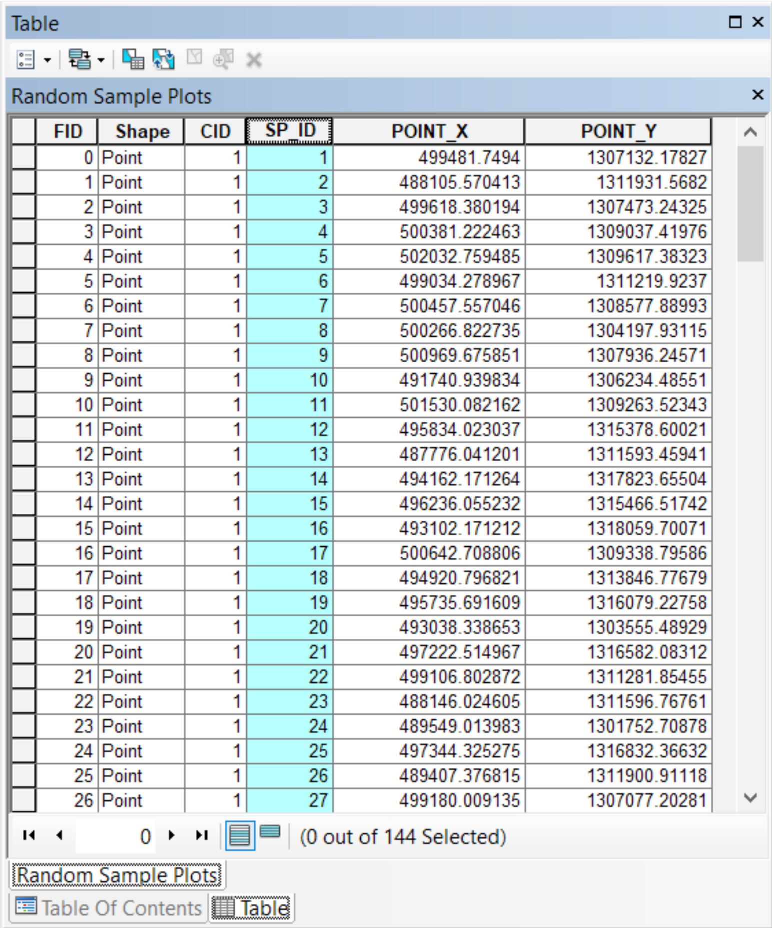
The positions and coordinates of random sample plots are transferred to the GPS to determine the field (Huy, Sharma and Quang, 2013), using the steps in Box 10.

Box 10. Steps to upload the coordinates of the random sample plots to the GPS

Step 1: Create a sample ID and X/Y coordinates of all the random plots in ArcGIS.

In the attribute table of the map of random plots, open a new field for the sample plot identification (e.g. 'SP ID') using Field Calculator to assign a number to each point using: SP ID = FID +1 (see the table below).

Use the 'Add XY Coordinates' tool to calculate and add coordinates of the X/Y fields for each random plot. The results are shown in the table below.



Table

Random Sample Plots

FID	Shape	CID	SP_ID	POINT_X	POINT_Y
0	Point	1	1	499481.7494	1307132.17827
1	Point	1	2	488105.570413	1311931.5682
2	Point	1	3	499618.380194	1307473.24325
3	Point	1	4	500381.222463	1309037.41976
4	Point	1	5	502032.759485	1309617.38323
5	Point	1	6	499034.278967	1311219.9237
6	Point	1	7	500457.557046	1308577.88993
7	Point	1	8	500266.822735	1304197.93115
8	Point	1	9	500969.675851	1307936.24571
9	Point	1	10	491740.939834	1306234.48551
10	Point	1	11	501530.082162	1309263.52343
11	Point	1	12	495834.023037	1315378.60021
12	Point	1	13	487776.041201	1311593.45941
13	Point	1	14	494162.171264	1317823.65504
14	Point	1	15	496236.055232	1315466.51742
15	Point	1	16	493102.171212	1318059.70071
16	Point	1	17	500642.708806	1309338.79586
17	Point	1	18	494920.796821	1313846.77679
18	Point	1	19	495735.691609	1316079.22758
19	Point	1	20	493038.338653	1303555.48929
20	Point	1	21	497222.514967	1316582.08312
21	Point	1	22	499106.802872	1311281.85455
22	Point	1	23	488146.024605	1311596.76761
23	Point	1	24	489549.013983	1301752.70878
24	Point	1	25	497344.325275	1316832.36632
25	Point	1	26	489407.376815	1311900.91118
26	Point	1	27	499180.009135	1307077.20281

0 (0 out of 144 Selected)

Random Sample Plots

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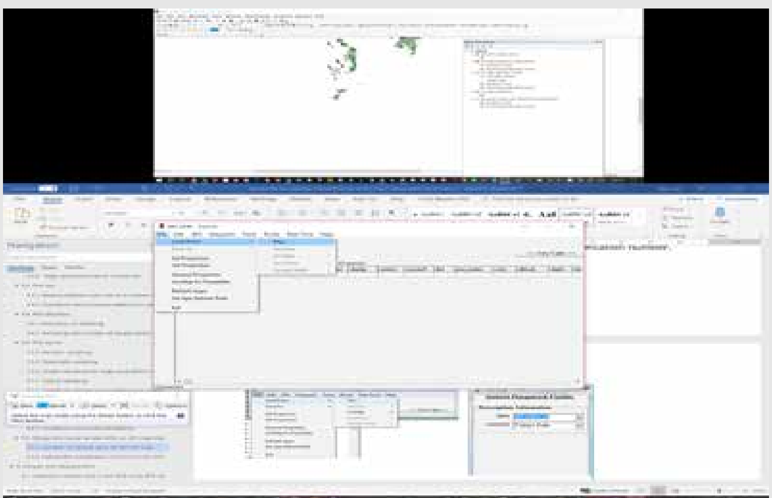
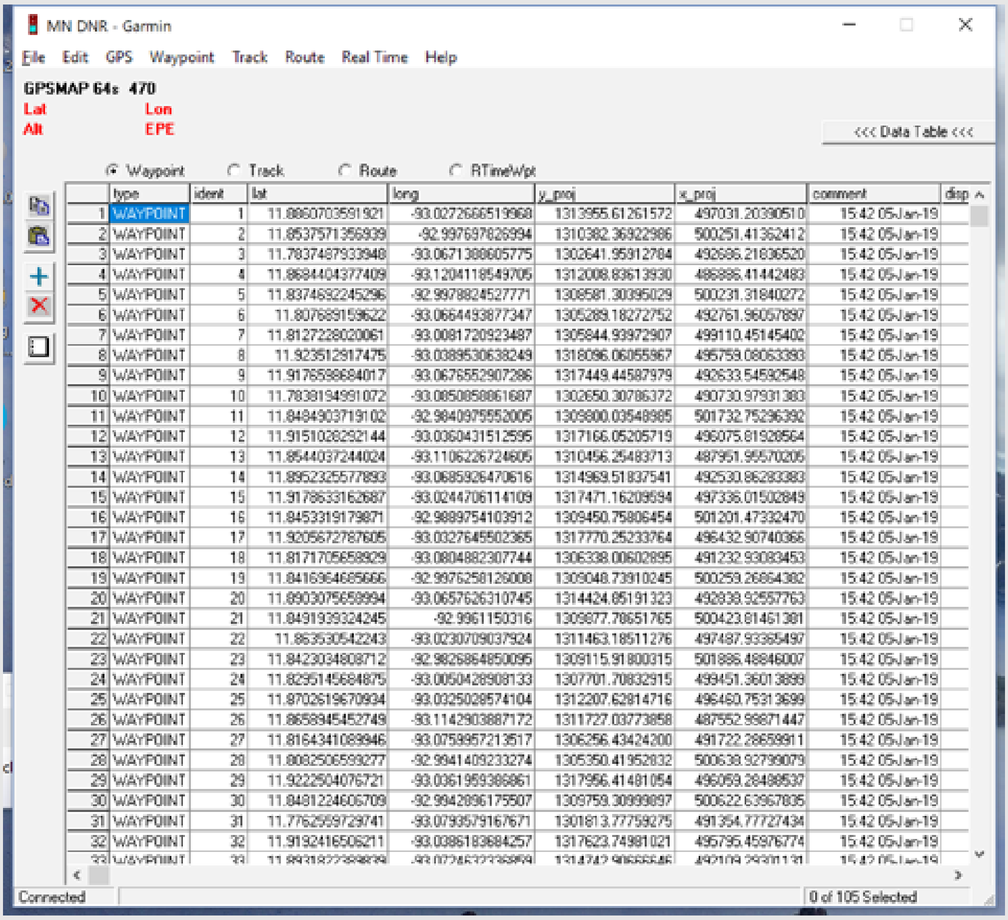
Step 2: Use DNRGarmin software to upload the waypoints with the X/Y coordinates of all the random plots to the GPS. Open DNRGarmin and set up the coordinate system: Select File/Set Projection. Load PRJ and select the file of the sample plot coordinates (see below).

Open the data set of established random plot coordinates: File/Load from/File ... Select the files in the shape file format to open the saved coordinates. In the identity field, select the field that has the plot identification information (e.g. 'SP ID') and then click OK (see below).

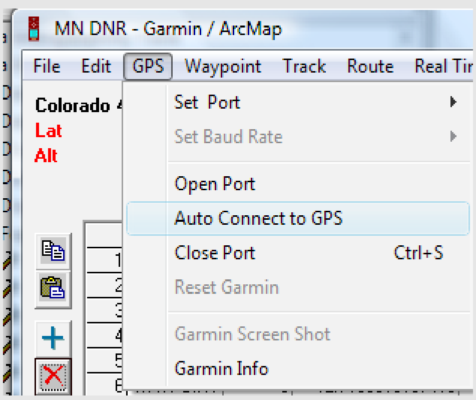


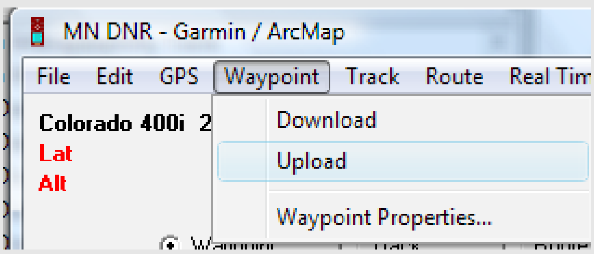
The result is a table that contains ID plots; the X/Y coordinates are shown below.



	type	ident	lat	long	y_proj	x_proj	comment	disp
1	WAYPOINT	1	11.8860703591921	-93.0272666519968	1313955.61261572	497031.20390510	15:42 05-Jan-19	
2	WAYPOINT	2	11.8537571356939	-92.997697826994	1310382.36922986	500251.41362412	15:42 05-Jan-19	
3	WAYPOINT	3	11.7837487933948	-93.0671388605775	1302641.95912784	492686.21836520	15:42 05-Jan-19	
4	WAYPOINT	4	11.8684404377409	-93.1204118549705	1312008.83613930	486886.41442483	15:42 05-Jan-19	
5	WAYPOINT	5	11.8374692245296	-92.9978824527771	1308581.30395029	500231.31840272	15:42 05-Jan-19	
6	WAYPOINT	6	11.807689159622	-93.0664493877347	1305289.18272752	492761.96057897	15:42 05-Jan-19	
7	WAYPOINT	7	11.8127228020061	-93.0081720923487	1305844.93972907	499110.45145402	15:42 05-Jan-19	
8	WAYPOINT	8	11.923512917475	-93.0389530638249	1318096.06055967	495759.08063393	15:42 05-Jan-19	
9	WAYPOINT	9	11.9176598684017	-93.0676552907286	1317449.44587979	492633.54592548	15:42 05-Jan-19	
10	WAYPOINT	10	11.7838194991072	-93.0850858061687	1302650.30786372	490730.97931383	15:42 05-Jan-19	
11	WAYPOINT	11	11.8484903719102	-92.9840975552005	1309800.03548985	501732.75296392	15:42 05-Jan-19	
12	WAYPOINT	12	11.915102829144	-93.0060431512595	1317166.05205719	496075.81928564	15:42 05-Jan-19	
13	WAYPOINT	13	11.8544037244024	-93.1106226724605	1310456.25483713	487951.95570205	15:42 05-Jan-19	
14	WAYPOINT	14	11.8952325577893	-93.0685926470616	1314969.51837541	492530.86283383	15:42 05-Jan-19	
15	WAYPOINT	15	11.9178633162687	-93.0244706114109	1317471.16209594	497336.01502849	15:42 05-Jan-19	
16	WAYPOINT	16	11.8453319179871	-92.9889754103912	1309450.75806454	501201.47332470	15:42 05-Jan-19	
17	WAYPOINT	17	11.9205672787605	-93.0327645502365	1317770.25233764	496432.90740366	15:42 05-Jan-19	
18	WAYPOINT	18	11.8171705658929	-93.0804882307744	1306338.00602895	491232.93083453	15:42 05-Jan-19	
19	WAYPOINT	19	11.8416964685666	-92.9976258126008	1309048.73910245	500259.26864382	15:42 05-Jan-19	
20	WAYPOINT	20	11.8903075658994	-93.0657626310745	1314424.85191323	492838.92557763	15:42 05-Jan-19	
21	WAYPOINT	21	11.8491939324245	-92.9961150316	1309877.78651765	500423.81461381	15:42 05-Jan-19	
22	WAYPOINT	22	11.863530542243	-93.0230709037924	1311463.18511276	497487.93365497	15:42 05-Jan-19	
23	WAYPOINT	23	11.8423034808712	-92.9826864850095	1309115.91800315	501886.48846007	15:42 05-Jan-19	
24	WAYPOINT	24	11.8295145684875	-93.0050428908133	1307701.70832915	499451.36013899	15:42 05-Jan-19	
25	WAYPOINT	25	11.8702619670934	-93.0325028574104	1312207.62814716	496460.75313699	15:42 05-Jan-19	
26	WAYPOINT	26	11.8658945452749	-93.1142903887172	1311727.03773858	487552.99871447	15:42 05-Jan-19	
27	WAYPOINT	27	11.8164341089946	-93.0759957213517	1306256.43424200	491722.28659911	15:42 05-Jan-19	
28	WAYPOINT	28	11.8082506599277	-92.9941409233274	1305350.41952832	500638.92799079	15:42 05-Jan-19	
29	WAYPOINT	29	11.922250407672	-93.0361959386861	1317956.41481054	496059.28488537	15:42 05-Jan-19	
30	WAYPOINT	30	11.8481224606709	-92.9942896175507	1309759.30999897	500622.63967835	15:42 05-Jan-19	
31	WAYPOINT	31	11.7762959729741	-93.0793579167671	1301813.77759275	491354.77727434	15:42 05-Jan-19	
32	WAYPOINT	32	11.9192416506211	-93.0386183684257	1317623.74981021	495795.45976774	15:42 05-Jan-19	

The final step is to upload the data of sample plot coordinates to the GPS (see the tabs below):
- Connect to GPS: in DNR, GPS/Auto Connect to GPS
- Waypoint/Upload





The completion of these steps will transfer the coordinates of the sample plots to the GPS. Use the 'GoTo' function in the GPS to navigate the sample plots in the field later.

4. Sample plot measurement

4.1. Determining sample plots in the field using GPS

Since the coordinates of random sample plots are loaded into the GPS, the navigation function of the GPS is used along with the compass to determine the location of the sample plots in the field (Huy, Sharma and Quang, 2013) (Figure 31). Box 11 demonstrates the procedure to determine the position of random plots in the fields using the GPS.

Figure 31. GPS and determining the position of random sample plots using GPS in the field (left to right, respectively) (Photos: Bao Huy, 2019).

Box 11. Using the GPS, map 60 CSx to determine the position of random sample plots in the field

A sheet of coordinates with the ID of sample plots and relevant information such as forest status, forest block, sub-forest compartment and forest compartment area along with the map of the random sample plots are prepared for checking in the field:

- Open the GPS and press the button Find/Waypoint/Enter to access Waypoint in GPS.
- From the list of plots, select the correct plot which is to be sampled.
- Press Goto and select off road (if in forest).
- Walk to the direction shown on the GPS. The GPS will alarm (make a sound or beep) when the destination plot is reached.
- The coordinates of the defined plot centre should be checked in the GPS and on the map.
- If camera is available, take a picture of the GPS while the GPS is showing the coordinate position.
- End the Goto function by pressing Menu and then select Stop Navigation.

Huy, Sharma and Quang (2013)

Navigate to the plot using the GPS; for circular plots, this must be the plot centre, and for square/rectangular plots, this must be the first corner of the plot (Petrova et al, 2010). If the permanent plot approach is applicable, the permanent marker in the field will be useful for locating the plots for repeated measurements. Take a picture of the plot centre with the plot marker and iron board with the plot information; plot coordinates and codes, for example, must be clearly visible (Huy, Sharma and Quang, 2013).

An important action for determining the position of the plots in the forests distributed across the mountains with complex terrain is to determine if the plot has to be moved due to mixed slopes. At the new position of the plot centre/corner, mark a 'waypoint' on the GPS and record the GPS coordinates along with the plot ID on the data sheet. Box 12 is a useful guideline (see Petrova et al, 2010) for selecting appropriate positions and establishing the plot in an area that is either on a slope or on level ground.

Box 12. Select and establish the plot in an area that is either on a slope or on level ground
(Petrova et al, 2010, p.72)

Occasionally the plot will fall into an area of mixed slopes. One portion of the plot might be on level ground but another portion might fall on a hillside. Since the plot dimensions are a function of slope, it is important to establish the plot in an area that is either on a slope or on level ground. The potential for error is too high to have a portion on sloping land and the other portion on level ground. Therefore, prior to establishing a plot, the crew chief should determine if any portion of the plot will be on a slope > 10 per cent. If more than 50 per cent of the plot falls on a slope > 10 per cent, move the plot so that the entire plot is located on the slope. If more than 50 per cent of the plot is located on level ground, but the rest of the area is on a hillside (slope > 10 per cent), move the plot centre/corner so that the entire plot will fall on level ground.

4.2. Establishing a sample plot in the field

4.2.1. Establishing a circular plot

i) Using equipment to measure distance

Usually, when applying a circular plot in the timber forest investigation, we need not establish the plot; DME or LaserAce equipment alone will suffice to determine the distance from a plant to the centre of the plot to ascertain which plant is in the circular plot and should be measured (Figure 32). However, for bamboo forests, the bamboo culms are often dense, so the use of DME or LaserAce becomes difficult or cannot be done at all. However, for running bamboo with no dense culms, these tools may be effective.

When using DME or LaserAce, the only requirement is to place the DME stand or a stake in the centre point of the plot. Box 13 explains briefly how to measure distance using DME. To learn how to use LaserAce™ 1000 to measure distance, please read its User Guide (Trimble, 2011).

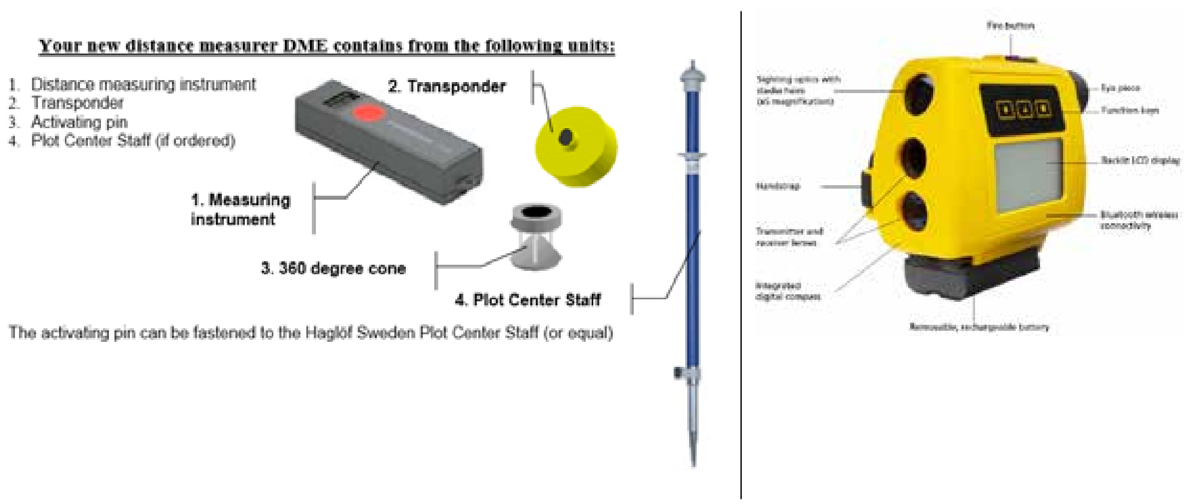


Figure 32. Equipment to measure distance; DME and LaserAce™ 1000 equipment (left to right, respectively).

Box 13. Using DME to measure distance

Start and place the transponder at the place for which you need to know the distance. When the transponder is not in use, turn the transponder off.

To obtain a correct distance, direct the measuring instrument toward the transponder and press the red button one time. Four lines [- - - -] will show in the display. After a few seconds the distance will appear in the display.

If the measuring instrument does not obtain any answering signals from the transponder, the four lines [- - - -] in the display will appear and no distance will be featured. Please check that the transponder is set, the batteries are working or if other errors may have occurred. If the red button is kept pressed down and you move slowly backwards, the instrument will measure the increase (or decrease if moving forward) continuously.

Source: DME User Manual (2001, p. 4)

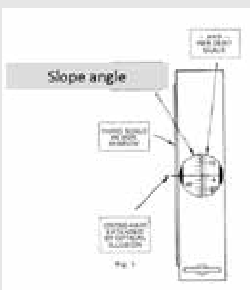
ii) Using knotted ropes

Prepare four ropes with two coloured knots. Use different colours for individual knots. Put each knot at an interval equivalent to the radius of the plot. For example, using a circular plot 100 m^2 with radius R = 5.64 m, make a yellow knot 5.64 m and add one more red knot, which can be moved to lengthen the radius of the plot on the slope (Figure 33).

Figure 33. Knotted rope for a circular plot of 100 m^2 with a yellow knot at a radius of 5.64 m and add one more removable red knot to lengthen the radius of the plot on the slope.

Using a stake, mark the GPS waypoint as the centre point of the plot. Measure the radius of the plot using knotted ropes and the slope of the ground using Suunto Clinometer in eight directions (i.e. every time the rope is laid on the ground along the plot radius). Box 14 shows how to use Suunto for measuring the slope (Figure 34).

Box 14. Using Suunto Clinometer to measure the slope angle



Ask one field crew member to stand on the slope. Aim the clinometer toward the head of a person standing above or below the slope to create the line of sight. The line of sight must be parallel with the slope surface. The indicator on the left of the clinometer shows the slope angle.

(Huy, Sharma and Quang, 2013, p. 17)

Figure 34. Suunto Clinometer, obtaining a slope using the clinometer (left to right, respectively) (Photos: Bao Huy, 2019).

A table with slope-corrected horizontal distances can be taken to the field (Table 26). The knot for representing the radius of the plot on the slope (> 10°) must be corrected accordingly. For example, if a plot with a radius of 5.64 m is located at a slope of 20 degrees, the removable red knot should be placed at the additional length of 0.36 m distance (Figure 35).

Figure 35. Using knotted ropes to establish a circular plot and adding extra radius distance to the slope (left to right, respectively) (Photos: Bao Huy, 2019).

Table 26. Additional distances in m at different radii and lengths for circular/square plots located on slopes over 10°

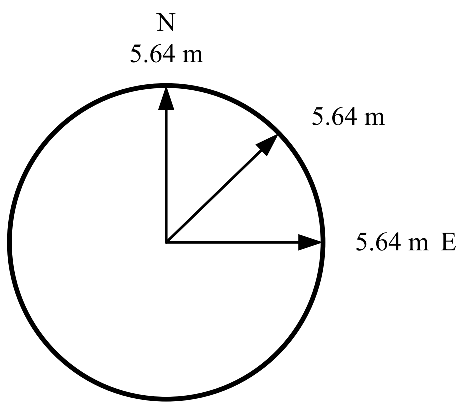
Slope (degree)	Radius of circular plots (m)			Length of square plots (m)		
	5.64	7.98	11.28	10.00	14.14	20.00
10	0.09	0.12	0.17	0.15	0.22	0.31
12	0.13	0.18	0.25	0.22	0.32	0.45
14	0.17	0.24	0.35	0.31	0.43	0.61
16	0.23	0.32	0.45	0.40	0.57	0.81
18	0.29	0.41	0.58	0.51	0.73	1.03
20	0.36	0.51	0.72	0.64	0.91	1.28
22	0.44	0.63	0.89	0.79	1.11	1.57
24	0.53	0.76	1.07	0.95	1.34	1.89
26	0.64	0.90	1.27	1.13	1.59	2.25
28	0.75	1.06	1.50	1.33	1.87	2.65
30	0.87	1.23	1.75	1.55	2.19	3.09

Slope (degree)	Radius of circular plots (m)			Length of square plots (m)		
	5.64	7.98	11.28	10.00	14.14	20.00
32	1.01	1.43	2.02	1.79	2.53	3.58
34	1.16	1.65	2.33	2.06	2.92	4.12
36	1.33	1.88	2.66	2.36	3.34	4.72
38	1.52	2.15	3.04	2.69	3.80	5.38
40	1.72	2.44	3.45	3.05	4.32	6.11
42	1.95	2.76	3.90	3.46	4.89	6.91
44	2.20	3.11	4.40	3.90	5.52	7.80
46	2.48	3.51	4.96	4.40	6.22	8.79
48	2.79	3.95	5.58	4.94	6.99	9.89
50	3.14	4.43	6.27	5.56	7.86	11.11

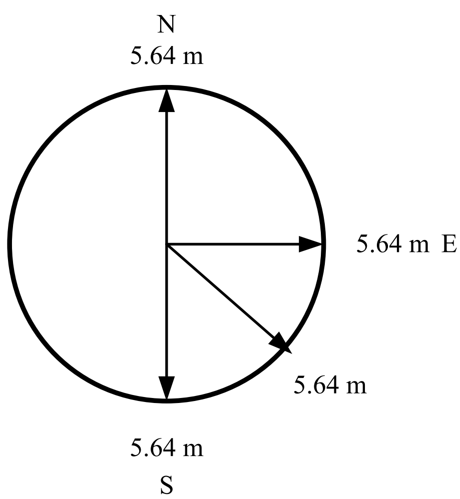
Note: *Additional distances are only necessary when the slope is over 10°. Additional distance: D = L × (1/Cosa – 1), where L is the radius or length of the circle or square plot, respectively, and a is the slope in degrees.*

The following segment outlines the four steps of establishing and measuring the circular plot using knotted ropes (Huy, Sharma and Quang, 2013) (an example of circular plot 100m^2 with a radius of 5.64 m):

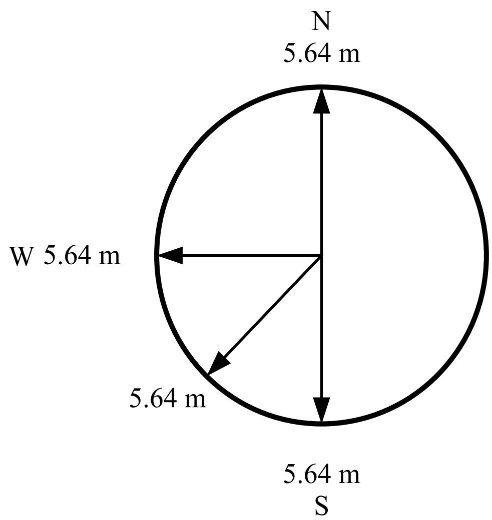
1. First, stretch one rope from the centre point of the plot towards the north direction. Stretch another rope to the east direction, and stretch a third rope at 45˚N between the first and second rope to establish two segments from north to east. The measurement is carried out from the left to the right segment (i.e. clockwise) and from the centre towards the plot radius..



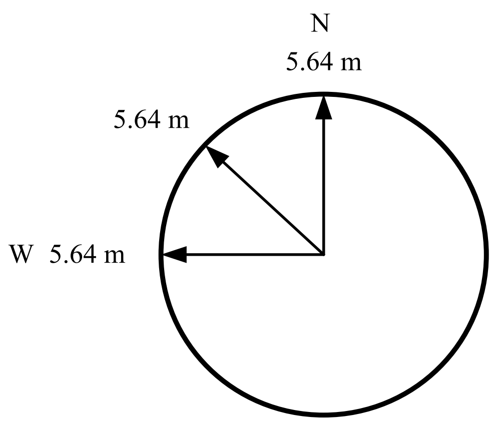
2. Second, keeping the north and the east ropes fixed in position, move the rope that stood in between toward the south direction (opposite to north). Then, stretch a fourth rope between the south and the east to create two segments in the south and the east. Measure from the left to the right segment and from the centre towards the plot radius.



3. Third, keeping the north and south ropes fixed in position, move the rope in the east to the west. Then move the rope that was between the east and the south to between the south and the west. Measure from the left to the right segment and from the centre towards the plot radius.



4. Finally, keeping the ropes in the north and the west fixed in position, place another rope between the west and the north. Measure from the left to the right segment and from the centre towards the plot radius.



4.2.2. Establishing square and rectangular plots

Prepare three knotted ropes; one rope is for making the central line of the plot. Put a fixed yellow knot at an interval equivalent to the length of the square plot and add one removable red knot that can be moved to lengthen the square plot on the slope. The other two knotted ropes are set an interval equivalent to the length of the square plot; thus, there are three fixed yellow knots in the middle and at either end of the rope.

To start establishing the square and rectangular plots using a stake, mark the GPS waypoint at the starting point of the central line of the plot (Figures 36 and 37) and then determine the direction of the slope by using a compass; the central line of the plot should be parallel with the slope direction.

Stretch the rope for the central line towards the slope direction and use a stake to mark the end of the length of the plot at the fixed yellow knots (Figure 36, left); for slopes, measure the slope of the ground using the Suunto Clinometer (Figure 34) and then adjust the plot length accordingly by moving a removable red knot (Figure 36, right) the extra length of distance presented in Table 26.

At either end of the central knotted rope already set up, stretch two ropes perpendicular to the centre rope and their middle points located on the centre line. Finally, mark with stakes the ends of the plot length with the yellow fixed knots (Figure 36).

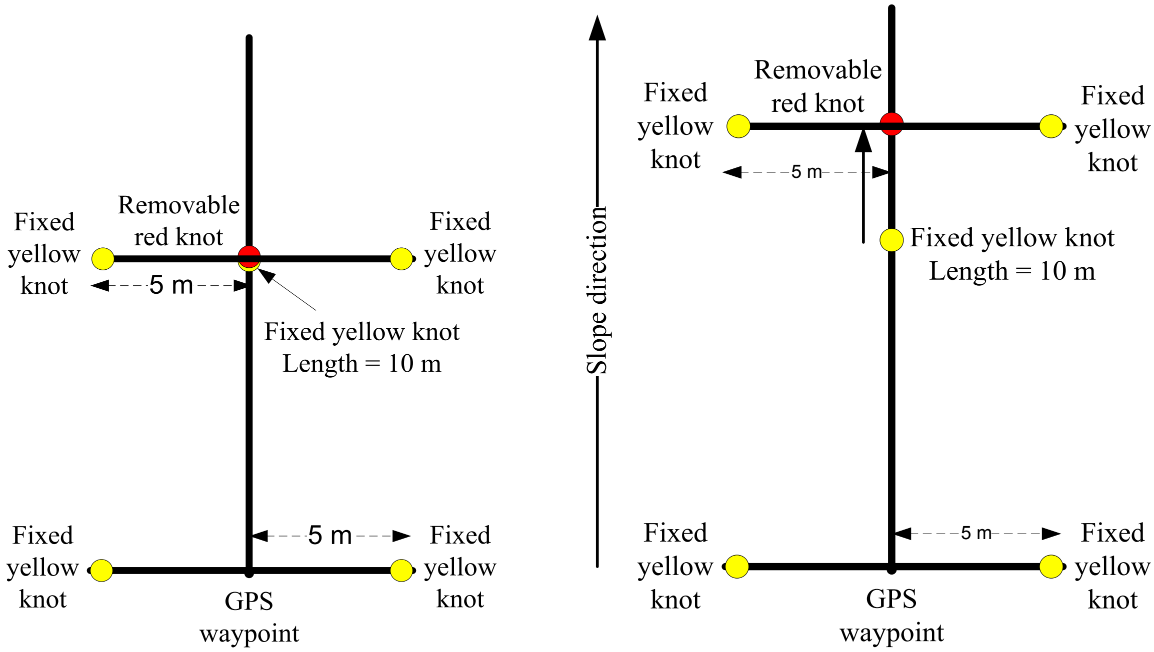


Figure 36. Using knotted ropes to establish square plots; on flat land and on sloping land (left to right, respectively; an example of the plot size of 100 m^2).

Figure 37. Forming the square plot, using knotted ropes.

4.2.3. Clump-based sampling

At the GPS waypoint of the plot, determine the nearest bamboo clump; from there, measure five distances of six nearest bamboo clumps sequentially, as shown in Figures 38 and 39.

From the average distance between the bamboo clumps, calculate the number of bamboo clumps per ha. For plantation of climping bamboo, there is no need to measure distances of six nearest bamboo clumps, because the density of clumps is calculated based on distance of clump to clump in row and distance between the rows. Choose the third and fifth clumps to count the total culms per clump and measure the average culms.

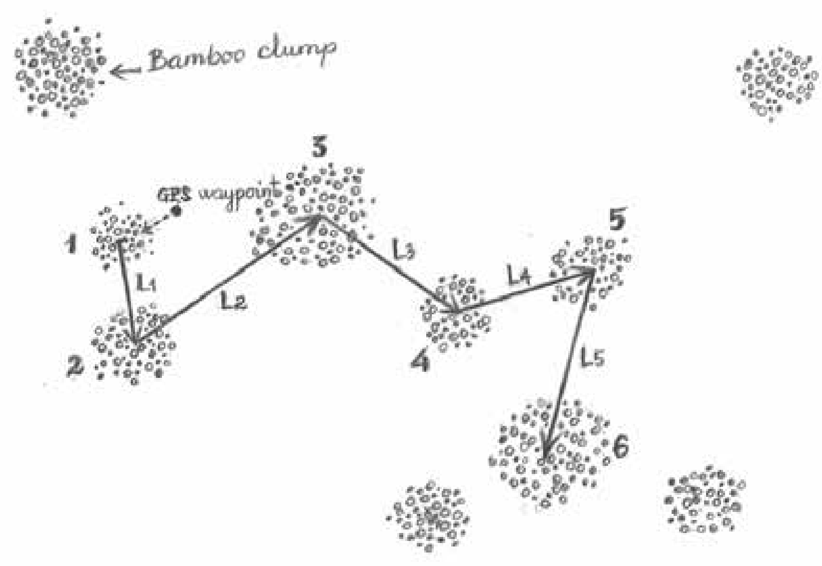


Figure 38. Clump-based sampling for climbing bamboo with very dense culms (Sketch: Nguyen Thi Thao, 2019).

Figure 39. Clump-based sampling: measuring distances from a clump to the nearest neighbouring clump (Photos: Bao Huy, 2018).

4.3.2. Edge correction

In cases when the centre of the plots falls near the edge of the stand (including voids, such as roads, lakes or power lines) and part of the plot is outside the stand, if possible, either move the plot to a neighbouring location, so that it is completely in the stand (Lackmann, 2011), or apply the method of the half-plot.

The half-plot method is described according to the following steps (Northwest Natural Resource Group, 2014) (see Figure 40):

- Draw a line through the centre of the plot and parallel to the stand edge boundary to divide the plot into two halves.
- Ignore all the plants in the half of the plot that fall partially outside of the stand.
- Double count the plants in the half plot that is entirely in the stand by recording each bamboo culm twice.

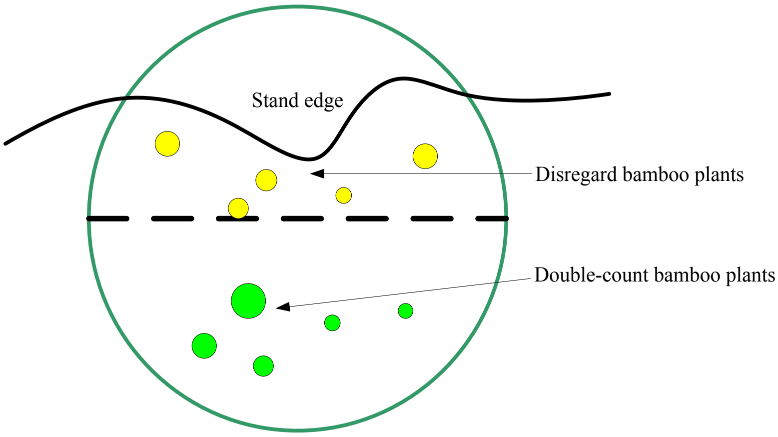


Figure 40. The half-plot method to correct the stand edge.

4.3. Measuring variables within the sample plot and taking samples

4.3.1. For AGB_{bamboo} – non-destructive measurement

The variables that need to be measured in the field depend on the predictors of the selected allometric equations for estimating AGB_{bamboo}. Divide the cases of measurement into two categories: (a) culm-based measurement in sample plots and (b) clump-based measurement.

i) Culm measurement in sample plots

This measurement is used for running bamboo or climbing bamboo with no dense culms. Measure the D (cm) and H (m) and identify the age of the bamboo culm (A, year) in sample plots and record the data in the sheet shown in Table 27.

- *Measure D (cm)*

The tool for measuring D includes diameter measurement tape (i.e. D-tape) or electronic callipers (Figure 41). Use the D-tape in case the bamboo diameter is larger than 3 cm; for smaller than 3-cm cases, the electronic calipers should be used to measure D accurately.

Measure all the bamboo culms in the plot using the D-tape or electronic calipers. Mark the culms measured with chalk or a coloured pen to avoid missing or replacing the measurement.

Diameter measuring tape (D-tape)

Electronic calipers

Figure 41. Measuring D using D-tape or electronic calipers (Photos: Bao Huy, 2019).

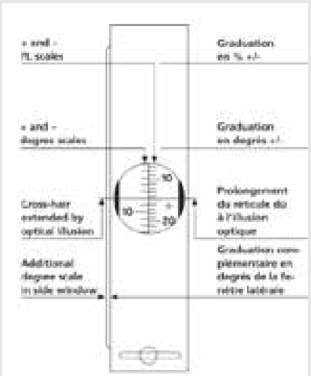
- *Measure H (m)*

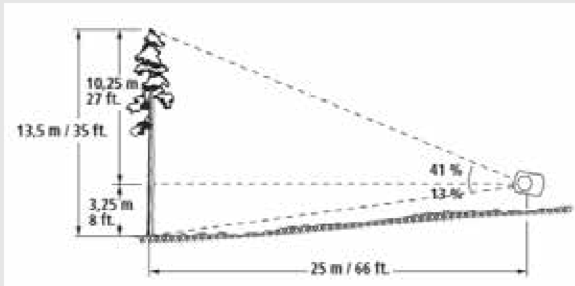
There are many tools and equipment to measure H, the most popular of which is the Suunto tool, which is used in forest inventory. There are also precision-measuring laser tools for the plant height (e.g. LaserAce™ 1000) (Figure 42). Box 15 provides a brief note on using Suunto to obtain the plant height. To learn how to use LaserAce™ 1000 to measure the height of the plant, you may read its User Guide (Trimble, 2011). There is no need to measure the height of all the culms in the plot because bamboo reaches its maximum height in the first year. Measure the height of the representing bamboos for each clump.

Figure 42. Suunto and LaserAce equipment to measure H (left to right, respectively) (Photos: Bao Huy, 2019).

Box 15. Using Suunto equipment to measure H

Total height is the sum percentage of the horizontal distance. For example, if the apex reading is 41 per cent and the ground reading 13 per cent, the total height of the plant measured from distance of 25 m is (41 + 13)/100 × 25 m = 13.5 m.





Source: Suunto, User Guide, p. 13

- *Determining A (year)*

The bamboo culm age can be identified based on certain features of the culm sheath, the development of branches and leaves, the external colour of the culm, etc. (Kaushal et al, 2018). The bamboo culm ages can be divided into 1, 2, 3, 4 and 5 years old (including culms more than five years old) (Yen, Ji and Lee, 2010). Box 16 describes the features that can be used to determine the bamboo culm age for *Bambusa* genus (Huy, Sharma and Quang, 2013). Based on the guidelines for determining bamboo culm age for each bamboo species available as well as the experience of the local people, the age of all the culms in the plot needs to be identified.

Box 16. The features used to determine the bamboo culm age for *Bambusa* genus

- *First year of age:* The bamboo culm that finishes its growth period in the previous rainy season is characterised as follows:
  - The sheath still exists on culm, usually near the root.
  - The culm colour is light green and covered by a layer of ‘white powder’; however, lichen has not developed.
  - Many small branches appear along the main culm. Very few young branches occur on the upper culm.
- *Second year of age*:
  - The sheath is not present.
  - The culm colour is green. It is covered by a layer of ‘white powder’; however, it is less than that of the first year. Minimal lichen or none is present near the root.
  - Many branches have appeared. Young sub-branches may occur.
- *Third year of age*:
  - The main culm colour is dark green; lichens cover 30-40 per cent of the culm surface, creating white spots in the culm. The green colour of culm is still visible.
  - The branches are mainly on top of the tree. The old main branches turn dark green with spotted lichen. Sub-branches may show.

- *Fourth year of age*:
  - Culm is white due to the strong presence of lichen (accounts for 70-80 per cent of culm surface).
  - The branches are limited to the upper culm. The old, main branches turn dark green with spotted lichen.
- *Five years and more:*
  - The culm colour changes to yellow, and dense lichen develops along the culm.
  - Decay and fall are apparent.

Huy, Sharma and Quang (2013, p. 32)

Table 27. Sheet for bamboo culm measurement in the sample plot

Plot information

Plot ID:	Coordinate: X: Y:
Plot size: Plot shape:	Forest type:
Average bamboo culm height (m):	Species of bamboo:
Slope (degree):	Altitude (m):
Recorded by:	Date:

Data of bamboo culm measurement

Culm ID	Culm age (A, year)	Culm diameter at breast height (D, cm)	Culm ID	Culm age (year)	Culm diameter (D, cm)

Note: *Record all variables with one decimal place except A.*

ii) Clump measurement using clump-based sampling

This measurement is used for clumping bamboo with very dense culms, using the clump-based sampling strategy.

Measure five distances of six nearest bamboo clumps, if it is clumping bamboo plantation, check and record distance of clump to clump in row and distance of row to row and, at the third and fifth clumps (Figure 38), count the total culms per age for each clump and measure D and H of three average culms per age for each clump. Record the measured data in Table 28.

Table 28. Sheet for average bamboo culm measurement in clump-based sampling

Plot information

Plot ID:	Coordinate: X: Y:
Forest type:	Species of bamboo:
Slope (degree):	Altitude (m):
Distances (m): L1: L2: L3: L4: L5: Distances (m) for plantation only: Clump to clump in row: Row to row:	Average bamboo culm height (m):
Recorded by:	Date:

Data of average bamboo culm measurement

Bamboo clump sample ID	A (year)	N_{culm}	D_1 (cm) / H_1 (m)	D_2 (cm) / H_2 (m)	D_3 (cm) / H_3 (m)
3rd clump	1				
	2				
	3				
	4				
	5				
5th clump	1				
	2				
	3				
	4				
	5				

Note: *Record all variables with one decimal place except A, N_{culm}.*

In case the selected equation has predictor(s) of bamboo clump variable(s) for estimating the total AGB_{clump}, measure the required clump variables of six clumps, such as G_{clump} or D_{clump}, H_{clump} and N_{culm} (Figure 38). For example, if we use model $AGB_{clump} = -3225.8 + 1730.4 \times D_{clump}$ (Kumar, Rajesh and Sudheesh, 2005), only the variable D_{clump} of six clumps are measured. Record the measured data of six clumps in Table 29.

Table 29. Sheet for culm measurement in clump-based sampling

Plot information

Plot ID:	Coordinate: X: Y:
Forest type:	Species of bamboo:
Slope (degree):	Altitude (m):
Distances (m): L1: L2: L3: L4: L5:	Distances (m) for plantation only: Clump to clump in row: Row to row:
Recorded by:	Date:

Data of average bamboo culm measurement

Bamboo clump sample ID	N_{culm}	G_{clump} (cm)	H_{clump} (m)
1			
2			
3			
4			
5			
6			

Note: *Record all variables with one decimal place except* N_{culm}.

4.3.2. For $AGB_{non\text{-}bamboo}$

Depending on the availability of the model for $AGB_{non\text{-}bamboo}$, there are two ways to collect field data: destructive and non-destructive.

i) For $AG_{Bnon\text{-}bamboo}$ – destructive method

The four-frame subplots of 0.5 m^2 (0.71 × 0.71 m) per sample plot are set up (see Figure 43) to harvest and weigh fresh non-bamboo vegetation by simple harvesting. Harvest all the non-bamboo plants in all the subplots and weigh the fresh biomass of non-bamboo vegetation in the field. Take a mixed sample of about 100-300 g from the four-frame subplots. The fresh mass of sample should be weighed exactly using the precision electronic scale to 0.1 g in the field (Figure 44). Bring the sample to the laboratory to determine the fresh-to-dry ratios. Record the data on non-bamboo vegetation in Table 30.

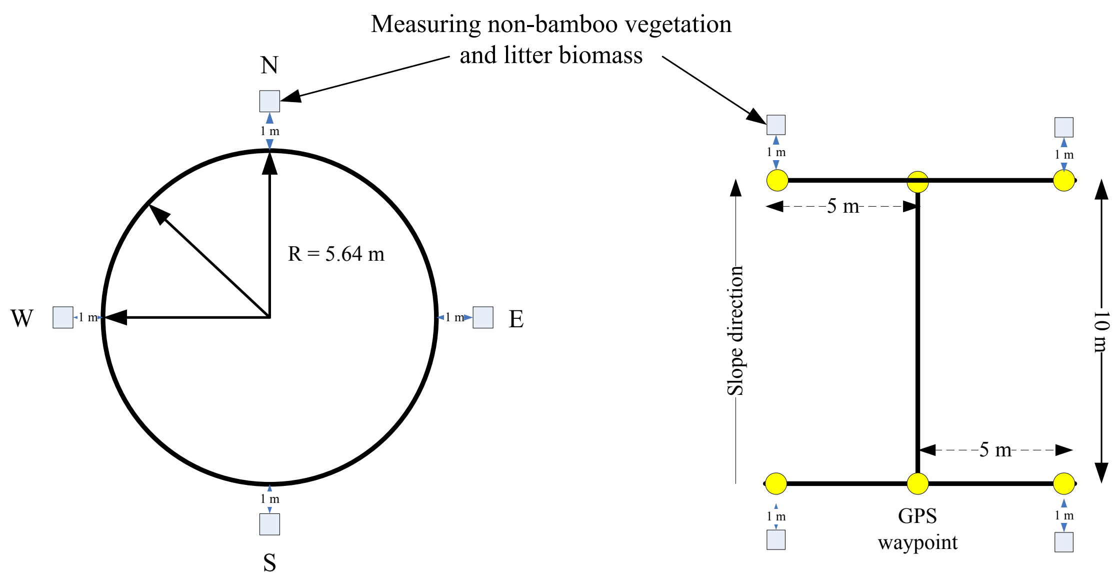


Figure 43. Locating four-frame subplots of 0.5 m^2 to measure the non-bamboo vegetation and B_{li}; for circular plot and for square plot (left to right, respectively) (an example of sample plot of 100 m^2).

Frame subplot of 0.5 m^2

Harvest non-bamboo vegetation

Weigh fresh non-bamboo vegetation biomass

Use precision electronic scale
to weigh fresh mass of sample

Figure 44. Activities to measure and take samples of non-bamboo vegetation (Photos: Bao Huy, 2019).

Table 30. Sheet of destructive measurement for $AGB_{non\text{-}bamboo}$

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Frame subplot ID	Fresh biomass of non-bamboo AGB (g)	Fresh mass of sample (g)
1		
2		
3		
4		

Note: *Record all variables with one decimal place.*

ii) For $AGB_{non\text{-}bamboo}$ – non-destructive method

This is only applicable when the allometric equations for shrubs are available; this is because the required data are the predictors of the biomass model of $AGB_{non\text{-}bamboo}$.

To collect data, use the same four-frame subplots of 0.5 m^2 (0.71 × 0.71 m) as the destructive method presented above and in Figure 43. Measure the predictors on each shrub plant in four of the frame subplots, which may be the CD of the north to south and east to west and/or H and/or D_0 (using an electronic caliper to 0.1 mm) (Figure 45). Use Table 31 to record the data measured.

Figure 45. Measuring the shrub, including predictors of CD, H and D_0 (left to right, respectively) (Photos: Bao Huy, 2019).

Table 31. Sheet of non-destructive measurement for $AGB_{non\text{-}bamboo}$

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Frame subplot ID	Species (if applicable)	CD (cm)		H (cm)	D_0 (mm)
		North to south	East to west		
1					
2					
3					
4					

Note: *Record all variables with one decimal place.*

4.3.3. For BGB_{bamboo}

There is no need to measure any variables in the field to estimate BGB_{bamboo}. The predictor(s) measured to estimate AGB_{bamboo} can also be used for the BGB_{bamboo} model. Alternatively, BGB_{bamboo} can be estimated via the available RSR (see Table 2).

4.3.4. For $BGB_{non\text{-}bamboo}$ – destructive method

The soil core is used to take soil samples and the fresh biomass of the root of non-bamboo vegetation. The soil core size is as follows: the diameter ranged from 4-10 cm and the length ranged from 6-20 cm; the average is 8 ×15 cm (Figure 46). Use the soil core to take soil samples at three soil layers: 0-30 cm, 30-50 cm and > 50 cm.

Weigh the fresh roots obtained from the soil cores in the field. Take a mixed sample about 100 g from three soil cores. The fresh mass of sample is weighed exactly by the precision electronic scale to 0.1 g in the field. Bring the destructive root sampled to laboratory to determine fresh-to-dry ratios (Figure 46). Record the data in the sheet in Table 32.

Figure 46. Soil core; using the soil core to take soil samples and roots of plants (Photos: Bao Huy, 2019).

Table 32. Sheet of destructive measurement for $BGB_{non\text{-}bamboo}$

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Soil layer	Fresh biomass of roots of BGB_{bamboo} (g)	Fresh mass of root sample (g)
0-30 cm		
30-50 cm		
> 50 cm		

Note: *Record all variables with one decimal place.*

4.3.5. For litter measurement

There are two ways to collect field data in litter measurement, which depend on the availability of allometric equations for B_{li} estimates.

i) For litter – destructive measurement

Use the four-frame subplots of 0.5 m^2 (0.71 × 0.71 m) per sample plot, which have the same measurement as $AGB_{non\text{-}bamboo}$ (Figure 43). Collect all the litter mass in frames of four subplots and weigh the fresh biomass of litter in the field. Take a mixed sample about 100 g from four subplots and bring it to the laboratory to determine the dry-to-fresh biomass ratios (Figure 47). Record the data measured in Table 33.

Figure 47. Collecting litter mass in a frame of 0.5 m^2 ; weighing the fresh litter and a mixed sample of litter (left to right, respectively) (Photos: Bao Huy, 2019).

Table 33. Sheet of destructive measurement for litter

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Frame subplot ID	Fresh biomass of litter (g)	Fresh mass of sample (g)
1		
2		
3		
4		

Note: *Record all variables with one decimal place.*

ii) For litter – non-destructive measurement

Adopt this non-destructive measurement in the field when the model to estimate biomass of litter is available.

Use the four-frame subplots of 0.5 m^2 (0.71 × 0.71 m) (Figure 43) per sample plot, which have the same destructive measurement of litter mentioned above to measure the litter data. Measure the predictor(s) mentioned in the allometric equation selected (e.g. LD (mm)) by using the electric caliper to 1 mm in each frame subplot. Record the data measured in Table 34.

Table 34. Sheet of non-destructive measurement for litter

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Frame subplot ID	LD (mm)
1	
2	
3	
4	

Note: *Record all variables with one decimal place.*

5. Frequency of measurement for bamboo forest carbon monitoring and assessment

The time series for forest inventory should be consistent to ensure that changes can be comparable (IPCC, 2003). The frequency of forest monitoring relates to the rate and extent of changes.The frequency of forest monitoring should be based on the dynamics of forest carbon pools and costs. In order to monitor changes in forest carbon pools, a five-year frequency is appropriate, while for SOC it may take up to 20 years (Pearson, Brown and Birdsey, 2007).

Meanwhile, forest areas often change constantly in developing countries, due to the need to clear forests to extend agricultural land or bamboo harvest; therefore, monitoring changes in forest areas need to be updated more frequently (e.g. annually).

Based on the frequency of forest inventory, monitoring in countries and dynamics in forest carbon pools, it is possible to apply the following:

- The frequency of total forest inventory should be every five years on the whole system of permanent or temporary sample plots.
- Update the changes in forest areas and forest statuses annually, using RS and GIS images.
- Depending on resources in each country and location, an annual revisit to one fifth (1/5) of the total sample would be advised.

6. QA and QC for field measurement

The input data set provided from the field is important because they can affect the reliability and accuracy of forest carbon estimations. Therefore, QA and QC should be considered and conducted carefully.

First, make sure that it is most appropriate to use the same method and consistent sources of data for all inventory years (IPCC, 2003, 2006).

The following activities are important and need to be done in QA and QC (Pearson, Brown and Birdsey, 2007; Lackmann, 2011; Petrova et al, 2010; Subedi et al, 2010; Huy, Sharma and Quang, 2013):

- Training for field working teams at the beginning is essential, ensuring that they understand the methods and that the tools and equipment are applied uniformly.
- Units used in the field must be consistent (e.g. the mass weight in g or kg and the diameter in mm or cm).
- Cross-checking and hot-checking in the field during the investigation is necessary to detect and correct errors.
- Blind check/independent validation: Validation by an independent third party is necessary. It is good practice to randomly resample 10-20 per cent of the total sample plots and 5-10 per cent of the total forest blocks by the independent party in order to identify errors in the sampling and to obtain the accuracy of the estimates. An error of < 10 per cent may be acceptable.

Organising QA and QC implementation may be done at the time of inventory or immediately after the forest inventory.

Chapter IV. DATA ANALYSIS AND REPORT ON BAMBOO FOREST CARBON STOCK CHANGES

1. Overview of data analysis and report on bamboo carbon stock changes

The estimates of the change of carbon stock include removals and emissions based on the analysis of two data sources, including activity data and emission factors. The activity data provide information on change of forest coverage and change of forest status; the emission factor informs the amount of carbon accumulation in the pools of forests.

To produce the outcomes of forest carbon inventory and assessment, a process of analysis and aggregate on data collected from two groups (i.e. activity data and emission factors) need to be performed (Figure 48).

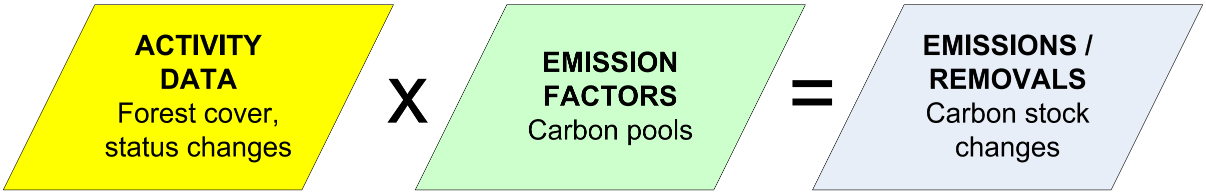


Figure 48. Combining activity data with emission factors to estimate forest carbon stock changes.

In other words, to compute the greenhouse gas (GHG) emissions (forest carbon emissions) or removals (forest carbon absorption), the amount of carbon at the two intervals should be determined.

Therefore, use the data collected from the field according to different methods – analysis and synthesis – to provide data on the carbon biomass of the pools per unit of forest area; use RS and GIS technology to provide information on deforestation and forest degradation. From these two results, the report on GHG emissions/removals will be generated.

2. Laboratory works

The work in the laboratory is to analyse the plant specimens to determine the fresh-to-dry mass ratios and the percentage of carbon sequestration in the dry biomass, most of which is to identify the fresh-to-dry mass ratios to convert the fresh biomass to dry, determining the carbon and CO_2 amount in biomass and commonly using carbon fraction of IPCC (2003, 2006).

The samples are split and oven-dried at 105°C (Figure 13) until constant weight to obtain the fresh-to-dry mass ratios of each sample to calculate dry biomass is achieved (Yen, Ji and Lee, 2010; Huy et al, 2016a, 2016b; Huy, Poudel and Temesgen, 2016).

From the samples gathered from the bamboo forest inventory, there are three kinds of samples that need analysis for fresh-to-dry mass ratios: $AGB_{non\text{-}bamboo}$, $BGB_{non\text{-}bamboo}$ and litter. The dry biomass = fresh-to-dry ratio × the fresh biomass and are recorded in Tables 35, 36 and 37.

Table 35. Fresh-to-dry ratio and dry biomass of $AGB_{non\text{-}bamboo}$

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Frame subplot ID	Fresh biomass of $AGB_{non\text{-}bamboo}$ (g)	Fresh-to-dry ratio	Dry biomass of $AGB_{non\text{-}bamboo}$ (g)
1			
2			
3			
4			

Note: *Record all variables with one decimal place. Ratios with three decimals.*

Table 36. Fresh-to-dry ratio and dry biomass of $BGB_{non\text{-}bamboo}$

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Soil layer	Fresh biomass of the roots of $BGB_{non\text{-}bamboo}$ (g)	Fresh-to-dry ratio	Dry biomass of the roots of $BGB_{non\text{-}bamboo}$ (g)
0-30 cm			
30-50 cm			
> 50 cm			

Note: *Record all variables with one decimal place except A, N_{culm}. Ratios with three decimals.*

Table 37. Fresh-to-dry ratio and dry biomass of litter

Plot ID: Coordinate: X: Y:

Recorded by: Date:

Frame subplot ID	Fresh biomass of litter (g)	Fresh-to-dry ratio	Dry biomass of litter (g)
1			
2			
3			
4			

Note: *Record all variables with one decimal place except A, N_{culm}. Ratios with three decimals.*

3. Calculation and estimation of bamboo stock, biomass and carbon sequestration in bamboo forest pools

This section introduces how to calculate average biomass and carbon in a forest unit area (e.g. ha) for each carbon pool.

The calculation needs to be performed separately for each type of forest. Thus, arrange and gather data and sample the plots according to forest stratification, such as bamboo forest, mixed bamboo forest, bamboo plantation or mixed bamboo and other tree plantations.

3.1. Estimating bamboo stock

The average of bamboo culms per diameter, age classes and total average bamboo culms per ha are estimated (see below), depending on the method of field measurement and data collected.

i) Estimating bamboo stock from data set of culm measurement in the sample plots

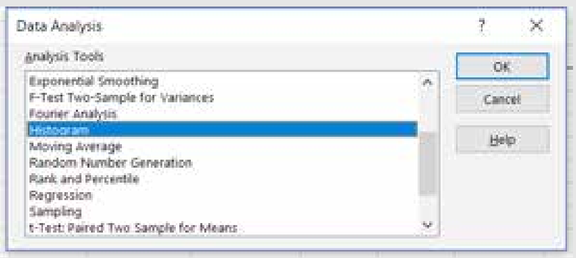
To process this data, the simplest way is to use Excel. Enter the entire bamboo data on D and A of all sample plots in Excel and use the histogram function to arrange the diameter and age distributions of all the plots and then convert them to ha. Box 17 shows the process in Excel.

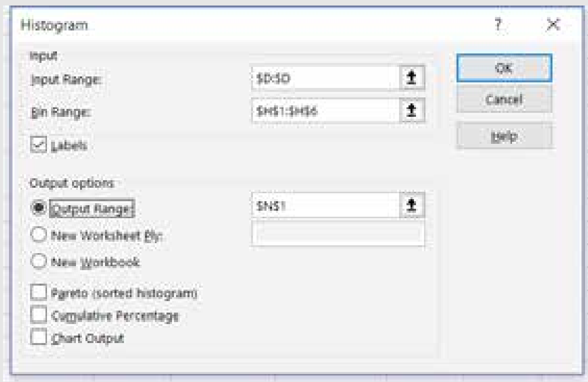
Box 17. Data analysis for diameter and age distributions performed in Excel

Enter the data of all the sample plots into an Excel spreadsheet, including fields of Plot ID, culm ID, D and A:

	A	B	C	D	E	F	G
1	Plot ID	Culm ID	D	A		D class	A class
2	L1	1	7.0	1		2	1
3	L1	2	7.2	1		4	2
4	L1	3	8.1	3		6	3
5	L1	4	8.6	1		8	4
6	L1	5	6.8	1		10	5
7	L1	6	7.9	2			

Use the histogram function in Excel to generate D and A distributions using the following tools:





Hence, D and A distributions of all plots will be done and then converted into ha.

Formulas to estimate the number of bamboo culms distributed in D or A class i per ha and total are as follows:

$$N_{iculm}ha^{-1} = \frac{10^4 \times \sum_1^n N_{iculm}}{n \times AP} \quad (38)$$

$$N_{culm}ha^{-1} = \sum N_{iculm}ha^{-1} \quad (39)$$

where $N_{iculm}ha^{-1}$ is the number of the bamboo culms distributed in D or A class i per ha; N_{iculm} is the number of the bamboo culms distributed in D or A class i of all plots; *n* is the number of the sample plots; *AP* is the area of the plot in m^2; $N_{culm}ha^{-1}$ is the averaged total bamboo culm per ha. This analysis provides information on bamboo stock, consisting of D and A distributions and total bamboo culms, averaged per ha for each forest stratum. Table 38 and Figure 49 are examples of calculation from 17 sample plots 100 m^2 for D and A distributions of *Bambusa procera* in the Central Highlands of Vietnam.

Table 38. D and A distributions and total bamboo culms averaged per ha

D class (cm)	$N_{i\ culm}$ all plots	$N_{i\ culm}$/ha
2	1	6
4	159	935
6	431	2,535
8	515	3,029
10	76	447
Total		6,953

A class	$N_{i\ culm}$ all plots	$N_{i\ culm}$/ha
1	88	518
2	180	1,059
3	285	1,676
4	276	1,624
5	312	1,835
> 5	41	241
Total		6,953

Note: *It is an example of 17 plots of 100 m² for Bambusa procera in the Central Highlands of Vietnam.*

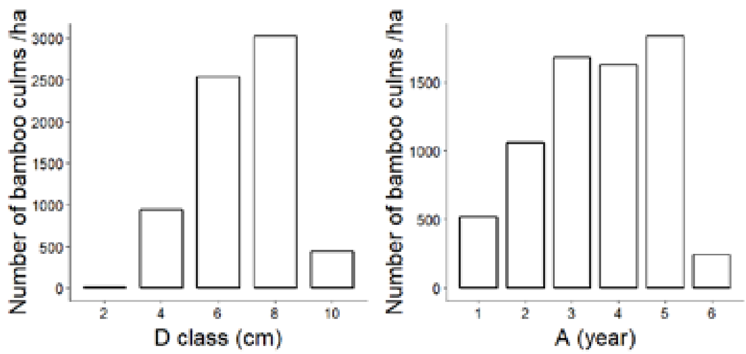


Figure 49. Diameter and age distributions per ha; an example of *Bambusa procera* in the Central Highlands of Vietnam.

ii) Estimating bamboo stock from a data set of clump measurements with clump-based sampling

In this case, first calculate the number of the bamboo clumps per ha based on the averaged distance among six nearest clumps according to the following formula:

$$N_{clump}\ \ ha^{-1} = \frac{1}{n}\sum_{1}^{n}\frac{10^4}{\left\{\frac{\sum_{i=1}^{5} L_i}{5}\right\}^2} \tag{40a}$$

where $N_{clump}\ ha^{-1}$ is the number of bamboo clump per ha, and L_i is the distances of the six nearest clumps in m (i = 1-5) and n is the number of the sample plots/points.

For clumping bamboo plantation, the density of the bamboo clumps per ha based on the distance of clump to clump in row and distance of row to row according to the following formula:

$$N_{clump}\ \ ha^{-1} = \frac{10^4}{L_{clump} \times\ L_{row}} \tag{40b}$$

where $N_{clump}\ ha^{-1}$ is the number of bamboo clump per ha, and L_{clump} is the distance in m of clump to clump in row and L_{row} is the distance in m of row to row.

Based on the average number of culms counted in clumps according to age class (A, year), calculate the number of culms per A class i according to the following formula:

$$N_{iculm}ha^{-1} = \sum_{1}^{n} N_{iculm} \times N_{clump}\ ha^{-1} \quad (41)$$

$$N_{culm}ha^{-1} = \sum N_{iculm}ha^{-1} \quad (42)$$

where $N_{iculm}ha^{-1}$ is the number of bamboo culms distributed in A class i per ha; N_{iculm} is the number of bamboo culms distributed in A class i; $N_{culm}\cdot ha^{-1}$ is the total of bamboo culms per ha and n is the number of the sample plots/points.

3.2. Estimating the AGB of a bamboo forest

3.2.1. Estimating AGB_{bamboo}

The AGB_{bamboo} ha^{-1} estimation depends on the selected allometric equations along with the data measurement in the field, as explained below.

i) *Estimating AGB_{bamboo} ha^{-1} based on the bamboo culm allometric equations and data set of bamboo culms from the sample plots*

Bamboo culm equations can be selected if they are available (e.g. in Table 21) or developed, as introduced in Section 6 of this manual.

Consider bamboo culm equations: $AGB = 0.269 \times D^{2.107}$ for *Bambusa nutans* (Yuen, Fung and Ziegler, 2017).

Enter the data of the bamboo culms of all the sample plots into Excel and then calculate culm AGB_{bamboo} in a new column based on the selected allometric equations (Table 39).

Table 39. Calculation of culm AGB_{bamboo} of all sample plots

Recorded by: Date:

Plot ID	Culm ID	Culm age (A, year)	Culm diameter at breast height (D, cm)	Culm AGB_{bamboo} (kg)

Note: *Record all variables with one decimal place except A.*

Use the following formula to estimate AGB_{bamboo} ha^{-1} in tonne:

$$AGB_{bamboo}ha^{-1} = \frac{10}{n \times AP} \sum_{j=1}^{m} AGB_{bamboo} \quad (43)$$

where *n* is the number of the sample plots; AP is the area of the plot in m^2; AGB_{bamboo} is culm AGB_{bamboo}, calculated via selected allometric equations in kg; and *j* is culm ID (j = 1-m).

ii) Estimating AGB_{bamboo} ha^{-1} based on the bamboo culm allometric equations and the averaged culm of clump sampling

Estimate AGB_{bamboo} ha^{-1} in tonne, which is based on average AGB_{bamboo}, estimated by the selected bamboo culm allometric equations via the average culm measured. Use the following formula:

$$AGB_{bamboo}ha^{-1} = \frac{1}{m}\sum_{1}^{m}\overline{AGB}_{bamboo} \times N_{culm}ha^{-1} \qquad (44)$$

where $\overline{AGB}_{bamboo}$ is the average culm AGB_{bamboo} in kg; N_{culm} ha^{-1} is the number of culms per ha, estimated by formula (42) and m is the number of the average bamboo culm measured.

iii) Estimating AGB_{bamboo} ha^{-1} based on the bamboo clump allometric equations and the clump sampling strategy

In this case, use the available equations to estimate AGB_{clump} (e.g. model: $AGB_{clump} = -3225.8 + 1730.4 \times D_{clump}$, Kumar, Rajesh and Sudheesh, 2005) for six clumps and then calculate AGB_{bamboo} ha^{-1} in tonne according to the following formula:

$$AGB_{bamboo}ha^{-1} = \frac{1}{n}\sum_{1}^{n}\frac{1}{6000}\sum_{1}^{6}AGB_{clump} \times N_{clump}ha^{-1} \qquad (45)$$

where AGB_{clump} is the bamboo clump biomass of six clumps in kg; N_{clump} ha^{-1} is the number of the clumps per ha, estimated by formula (40a or 40b) and n is the number of the sample plots/points.

3.2.2. Estimating $AGB_{non-bamboo}$

The $AGB_{non-bamboo}$ ha^{-1} estimation depends on either destructive or non-destructive measurement methods in the field.

i) Estimating $AGB_{nonbamboo}$ ha^{-1} based on the destructive biomass data in four-frame subplots

Estimate $AGB_{non-bamboo}$ ha^{-1} in tonne based on $AGB_{non-bamboo}$ from four-frame subplots and then convert them into ha according to the following formula:

$$AGB_{non-bamboo}ha^{-1} = \frac{1}{n}\sum_{1}^{n}\sum_{1}^{4}AGB_{non-bamboo} \times \frac{10^{-2}}{4 \times ASP} \qquad (46)$$

where $AGB_{non-bamboo}$ is biomass of non-bamboo vegetation in each four-frame subplot in g, and ASP is the area of subplot in m^2 and n is the number of the sample plots.

ii) Estimating $AGB_{nonbamboo}$ ha^{-1} based on non-destructive biomass data in four-frame subplots and using allometric equation

The selected equation for shrub plant biomass ($AGB_{non-bamboo}$) should have one or more predictor(s) such as CD (cm), H (cm) and/or D_0 (mm). Use the $AGB_{non-bamboo}$ equation to estimate $AGB_{non-bamboo}$ for each plant measured in the four subplots and then convert them into $AGB_{non-bamboo}$ ha^{-1} in tonne according to the following formula:

$$AGB_{non-bamboo}ha^{-1} = \frac{1}{n}\sum_{1}^{n}\sum_{j=1}^{m}AGB_{non-bamboo} \times \frac{10^{-2}}{4 \times ASP} \qquad (47)$$

where $AGB_{non\text{-}bamboo}$ is the biomass of non-bamboo plant in g, estimated by the equation; *j* is the ID of non-bamboo plant measured in four subplots (j = 1-m); and ASP is the area of subplot in m^2 and n is the number of the sample plots.

3.3. Estimating the BGB of a bamboo forest

3.3.1. Estimating BGB_{bamboo}

BGB_{bamboo} ha^{-1} can be estimated in the following two ways:

i) Using RSR

IPCC (2006) has provided the ratio of BGB to AGB with RSR = 0.20 for tropical/subtropical regions. Refer to Table 2 to select the appropriate RSR for species in the location to estimate BGB based on RSR according to the following formula:

$$BGB_{bamboo}\ ha^{-1} = RSR \times AGB_{bamboo}\ ha^{-1} \quad (48)$$

ii) Using allometric equations for plant BGB_{bamboo}

The most convenient method is to estimate BGB_{bamboo} ha^{-1} through the appropriate model available (e.g. the model):

$$BGB = 0.780 \times D^{0.708}.$$

For *Bambusa bambos* of Shanmughavel and Francis (1996), refer to Yuen, Fung and Ziegler (2017).

Apply the data set of bamboo plant measurements to the sample plots and use the following formula to estimate the BGB_{bamboo} ha^{-1} in tonne:

$$BGB_{bamboo} ha^{-1} = \frac{10}{n \times AP} \times \sum_{j=1}^{m} BGB_{bamboo} \quad (49)$$

where *n* is the number of the sample plots; *AP* is the area of the plot in m^2; BGB_{bamboo} is the culm BGB_{bamboo}, calculated via the selected allometric equation in kg; and *j* is culm ID (j = 1-m).

In fact, the collection of data on the bamboo root system is difficult and costly (Yuen, Fung and Ziegler, 2017), and very few models are available for estimating BGB_{bamboo}. Therefore, future investments in setting up BGB models for the bamboo species in the ecological regions are useful for estimating the important carbon pool of bamboo forests.

3.3.2. Estimating $BGB_{non\text{-}bamboo}$

Estimate the $BGB_{non\text{-}bamboo}$ ha^{-1} in tonne to the depth of 50 cm based on $BGB_{non\text{-}bamboo}$ from three soil cores, taken from three soil layers, and convert them into ha according to the following formula:

$$BGB_{non-bamboo} ha^{-1} = \frac{1}{n}\sum_{1}^{n}\sum_{1}^{3} BGB_{non-bamboo} \times \frac{5 \times 10^3}{3 \times V_{soil\ core}} \quad (50)$$

where $BGB_{non\text{-}bamboo}$ is the dry biomass of non-bamboo vegetation in each three-soil core in g, and $V_{soil\ core}$ is the volume in cm^3 of the soil core used to take the root biomass of non-bamboo and n is the number of the sample plots.

3.4. Estimating biomass in the litter pool of a bamboo forest (B_{li})

The estimation of biomass in litter per ha ($B_{li}ha^{-1}$) in tonne depends on either a destructive or non-destructive method of measurement in the field.

i) Estimating $B_{li}ha^{-1}$ based on destructive biomass data in four-frame subplots

Estimate $B_{li}ha^{-1}$ in tonne based on B_{li} from the four-frame subplots and then convert them into ha according to the following formula:

$$B_{li}ha^{-1} = \frac{1}{n}\sum_{1}^{n}\sum_{1}^{4} B_{li} \times \frac{10^{-2}}{4 \times ASP} \quad (51)$$

where B_{li} is the dry biomass of litter in each four-frame subplot in g, and *ASP* is the area of subplot in m^2 and n is the number of the sample plots.

ii) Estimating $B_{li}ha^{-1}$ based on non-destructive biomass data in four-frame subplots and using allometric equation

The equation for estimating the B_{li} should have the following general form: B_{li} = f(LD), where LD is the litter depth in mm. Apply that model to each frame subplot; the predictor is the depth of litter used to estimate B_{li} per subplot and convert it into $B_{li}ha^{-1}$ in tonne according to the following formula:

$$B_{li}ha^{-1} = \frac{1}{n}\sum_{1}^{n}\sum_{1}^{4} B_{li} \times \frac{10^{-2}}{4 \times ASP} \quad (52)$$

where B_{li} is the biomass of litter in g, estimated by the equation; and *ASP* is the area of the subplot in m^2 and n is the number of the sample plots.

Currently, there are very few models for estimating B_{li} = f (LD). IPCC (2003) recommends developing this model, where the litter layer is thicker than 5 cm. Developing the B_{li} model hardly incurs considerable costs, mainly because the collection and analysis of B_{li} data is straightforward.

4. Updating forest cover and status changes

Deforestation and forest degradation or forest planting and promotion of regenerative forests will affect the amount of CO_2 emission or absorption. Thus, updating the data of forest area and forest stratum is essential for reporting biomass carbon stock changes and emissions.

Applying RS analysis periodically helps to keep the map layer of forest land use up to date. Using the GIS techniques such as the intersection of the layers of the forest status with the layers of the administrative management unit, the forest owner will obtain the updated map and its database of forest area and forest status under each unit of management. Export the attribute table of the intersection map layer to Excel and use the Pivot function to easily create the report sheet on the forest status area according to the management units and different forest owners.

Table 40 and Figure 50 are examples of a bamboo forest map and its data set updated in 2017 in Lam Dong Province, according to administrative management levels.

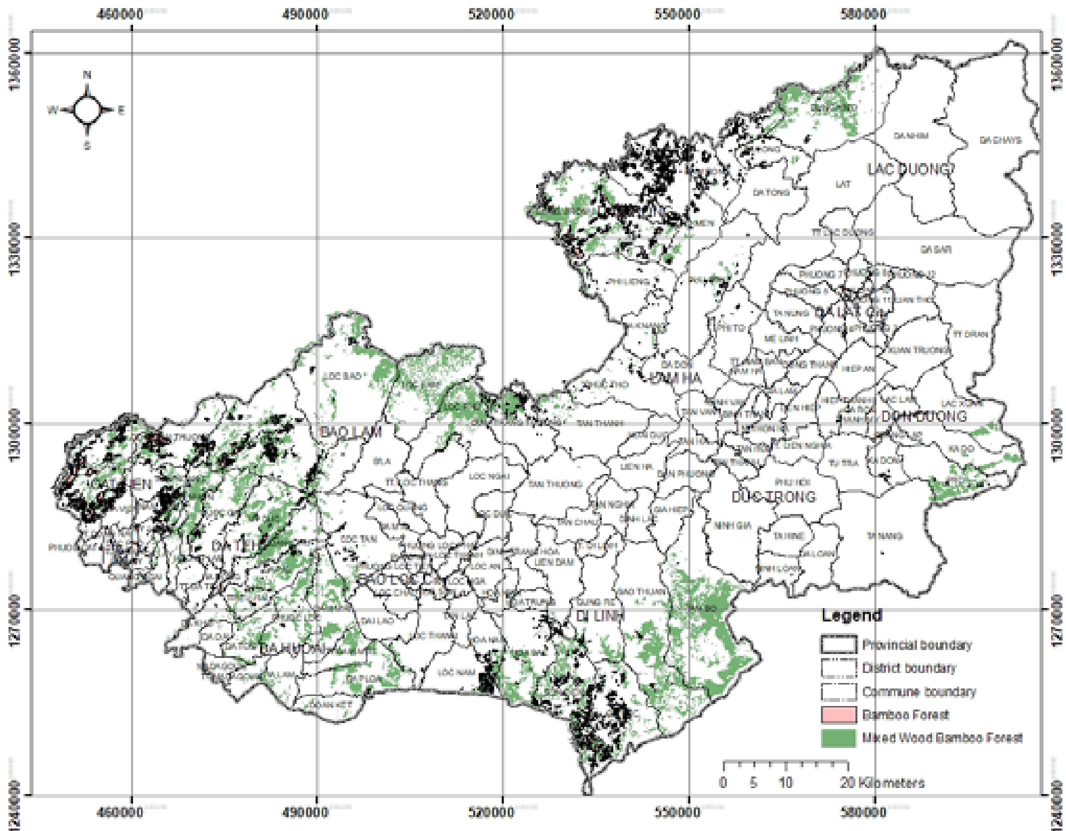


Figure 50. Map of bamboo forests located in different administrative levels in Lam Dong Province, Vietnam, 2017 (Source: VNForest, 2017).

Table 40. Bamboo forest area according to different administrative levels of district and commune in Lam Dong Province, Vietnam

Code district/ commune		Mixed bamboo forest (ha)	Bamboo forest (ha)	Total (ha)
673		24.7		24.7
	24844	24.7		24.7
674		6595.9	5159.9	11,755.7
	24853	228.4	332.3	560.6
	24856	175.4	129.8	305.2
	24859	100.1	406.4	506.4
	24874	5125.5	2189.3	7314.8
	24875	37.7	1131.0	1168.7
	24877	493.1	840.2	1333.3
	24886	405.6	127.5	533.1
	24889	30.2	3.6	33.7
675		5235.7	98.3	5334.0
	24848	11.4	42.6	54.0
	24850	5224.3	55.7	5280.0
676		1348.4	284.6	1633.0
	24880	479.4	111.6	591.0
	24883	17.1	32.2	49.3
	24895	7.4	33.9	41.3
	24898	243.3	52.7	295.9
	24904	2.0		2.0
	24907	599.3	54.3	653.5
677		3149.1	73.5	3222.6
	24934	491.1		491.1
	24943	627.0		627.0
	24949		27.0	27.0
	24952		2.1	2.1
	24955	2031.1	44.4	2075.5
678			3.4	3.4
	24989		2.4	2.4
	24997		1.0	1.0
679		26,011.0	2992.9	29,003.9
	25003	1672.0	251.5	1923.5
	25006	9.1		9.1
	25021	10,182.5	2.2	10,184.7
	25027	115.3	38.0	153.3
	25030	832.7	42.9	875.6
	25033	4990.2	33.0	5023.1
	25039		1.6	1.6
	25042	156.2	164.1	320.3
	25045	2249.1	107.7	2356.8
	25048	3922.3	718.4	4640.7
	25051	1881.6	1633.5	3515.1
680		18,908.1	1946.7	20,854.9

Code district/ commune		Mixed bamboo forest (ha)	Bamboo forest (ha)	Total (ha)
	25054	342.3		342.3
	25057	3850.8	62.6	3913.4
	25060	4566.3		4566.3
	25063	3406.8		3406.8
	25066	4963.3	1496.0	6459.3
	25078	1106.9	140.5	1247.3
	25090	329.5	10.5	340.0
	25093	342.2	237.2	579.3
681		9123.4	51.9	9175.3
	25096	926.8		926.8
	25099	209.0		209.0
	25102	2040.5	1.7	2042.2
	25105	514.1		514.1
	25108	766.0	2.6	768.5
	25111	43.0		43.0
	25114	2344.1	28.0	2372.1
	25117	125.9		125.9
	25120	176.9		176.9
	25123	1977.1	19.7	1996.7
682		12,552.1	536.9	13,089.0
	25126		12.6	12.6
	25129	1908.4	39.3	1947.7
	25132	2133.4	99.6	2233.0
	25135	2821.6	207.3	3028.8
	25138	2043.3	6.8	2050.1
	25141	636.2	43.6	679.8
	25144	327.8	17.4	345.2
	25147	660.0	26.0	686.0
	25153	192.1	6.0	198.1
	25156	1829.6	78.3	1907.8
683		4769.3	5148.0	9917.2
	25159		27.3	27.3
	25162	611.9	183.8	795.7
	25165	2834.3	3134.3	5968.7
	25168	57.6	388.4	446.0
	25171	24.7	274.6	299.3
	25174		141.9	141.9
	25177		55.4	55.4
	25180		2.6	2.6
	25183		4.2	4.2
	25189	29.2	2.9	32.1
	25192	1211.6	932.7	2144.3
Total (ha)		87,717.7	16,296.1	104,013.7

Note: *Source: VNForest (2017).*

5. Report on bamboo stocks and emissions or removals of CO_2 of bamboo forest

5.1. Report on bamboo stocks and carbon sequestration

From the outcome of a bamboo forest inventory, the following data should be synthesised and reported on regarding bamboo stocks and carbon sequestration.

5.1.1. Bamboo stocks

From the result of the estimation of bamboo density, according to D and A classes and N_{culm} ha^{-1}, combined with the area map of bamboo forests, calculate the total stock of bamboo according to different management units and forest owners:

$$N_{jculm} = N_{culm} ha^{-1} \times S_j \quad (53)$$

where $N_{j\,culm}$ is the total bamboo stocks in culms per management unit and owner j; S_j is the bamboo forest area of the management unit j, and $N_{culm} ha^{-1}$ is the total bamboo culms per ha.

5.1.2. Bamboo biomass and carbon stocks and CO_2 sequestration

Based on the estimated biomass for carbon pools of the bamboo forest (i.e. AGB, BGB and litter), use the carbon fraction (i.e. carbon = 0.47 × biomass and CO_2 = carbon × 3.67) (IPCC, 2006) and convert the biomass into carbon and a CO_2 equivalent; combined with the updated forest area, the total amount of carbon in each management unit and the forest owner will be reported. (In the future, to make the conversion of bamboo biomass into carbon more accurate, researching the set of carbon factions stratified by geographical region and/or bamboo species would be advised.)

Formulas to convert biomass into carbon and CO_2 equivalent per ha according to carbon pool are as follows:

- *AGB pool of bamboo forest:*

  + Above ground biomass per ha (AGB ha^{-1}):
  AGB $ha^{-1} = AGB_{bamboo} ha^{-1} + AGB_{non-bamboo} ha^{-1}$
  + Above ground carbon ha (AGC ha^{-1}):
  AGC ha^{-1} = 0.47 × AGB ha^{-1}
  + Above ground CO_2 per ha ($AGCO_2$ ha^{-1}):
  $AGCO_2$ ha^{-1} = 3.67 × AGC ha^{-1}

- *BGB pool of bamboo forest:*

  + Below ground biomass per ha (BGB ha^{-1}):
  BGB $ha^{-1} = BGB_{bamboo} ha^{-1} + BGB_{non-bamboo} ha^{-1}$
  + Below ground carbon per ha (BGC ha^{-1}):
  BGC ha^{-1} = 0.47 × BGB ha^{-1}
  + Below ground CO_2 per ha ($BGCO_2$ ha-1):

$BGCO_2\ ha^{-1} = 3.67 \times BGC\ ha^{-1}$

- *Litter pool of bamboo forest:*

+ Biomass in litter pool per ha: $B_{li}\ ha^{-1}$
+ Carbon in litter pool per ha ($C_{li}\ ha^{-1}$):
$C_{li}\ ha^{-1} = 0.47 \times BGB\ ha^{-1}$
+ CO_2 in litter pool per ha ($CO_{2li}\ ha^{-1}$):

$CO_{2li}\ ha^{-1} = 3.67 \times C_{li}\ ha^{-1}$

TB, total carbon (TC) and total CO2 equivalent (TCO2) in tonne per ha of the bamboo forest are as follows:

$TB\ ha^{-1} = AGB\ ha^{-1} + BGB\ ha^{-1} + B_{li}\ ha^{-1}$
$TC\ ha^{-1} = AGC\ ha^{-1} + BGC\ ha^{-1} + C_{li}\ ha^{-1}$

$TCO_2\ ha^{-1} = AGCO_2\ ha^{-1} + BGCO_2\ ha^{-1} + CO_{2li}\ ha^{-1}$

Using TB, carbon and CO2 per ha, combined with the bamboo forest area, will provide reports on gross biomass (TB), gross carbon (TC) and gross CO2 equivalent (TCO2) in tonne, where Sj is the bamboo forest area of the management unit j.

$TB = TB\ ha^{-1} \times S_j$
$TC = TC\ ha^{-1} \times S_j$
$TCO_2 = TC0_2\ ha^{-1} \times S_j$

As a result, the report on bamboo stocks and carbon sequestration can be recorded in the sheet shown in Table 41.

Table 41. Report on bamboo stocks and carbon sequestration under different forest management units

Management unit/forest owner	Bamboo forest area (ha)		N_{culm}	TC ha^{-1} (tonne)	TC (tonne)	Mixed bamboo forest		N_{culm}	TC ha^{-1} (tonne)	TC (tonne)
Province										
District										
….										
….										
Commune										
…..										
…..										
Forest Owner										
…..										
Grand total										

Table 42 demonstrates a sample sheet of the report on carbon sequestration in a mixed bamboo forest under different management units (e.g. district and commune). In this example, 87,717 ha of mixed bamboo forest in Lam Dong Province contains 617,357,031 million bamboo plants and sequesters approximately 3 million tonne of carbon, equal to over 10 million tonne of CO_2 equivalent.

Table 42. Report on bamboo stocks and carbon sequestration under different forest management units in Lam Dong Province, Vietnam

Code district/ code commune	Mixed bamboo forest (ha)	N_{culm} ha^{-1}	N_{culm} (mil. culm)	AGC of bamboo plant ha^{-1} (tonne)	TC (tonne)
District 673	**24.7**	**6953**	**171,948**	**32**	**792**
24844	24.7	6954	171,972	32	792
District 674	**6595.9**	**6955**	**45,874,137**	**32**	**211,113**
24853	228.4	6956	1,588,403	32	7309
24856	175.4	6957	1,220,188	32	5614
24859	100.1	6958	696,148	32	3202
24874	5125.5	6959	35,668,424	32	164,052
24875	37.7	6960	262,462	32	1207
24877	493.1	6961	3,432,748	32	15,784
24886	405.6	6962	2,823,439	32	12,980
24889	30.2	6963	209,934	32	965
District 675	**5235.7**	**6964**	**36,461,415**	**32**	**167,579**
24848	11.4	6965	79,540	32	366
24850	5224.3	6966	36,392,334	32	167,214
District 676	**1348.4**	**6967**	**9,394,372**	**32**	**43,159**
24880	479.4	6968	3,340,459	32	15,344
24883	17.1	6969	119,170	32	547
24895	7.4	6970	51,787	32	238
24898	243.3	6971	1,695,835	32	7786
24904	2.0	6972	13,665	32	63
24907	599.3	6973	4,178,570	32	19,180
District 677	**3149.1**	**6974**	**21,962,102**	**32**	**100,795**
24934	491.1	6975	3,425,492	32	15,719
24943	627.0	6976	4,373,812	32	20,068
24949		6977	-	32	-
24952		6978	-	32	-
24955	2031.1	6979	14,174,698	32	65,008
District 678		**6980**	**-**	**32**	**-**
24989		6981	-	32	-
24997		6982	-	32	-
District 679	**26,011.0**	**6983**	**181,634,464**	**32**	**832,532**
25003	1672.0	6984	11,677,248	32	53,516
25006	9.1	6985	63,703	32	292
25021	10,182.5	6986	71,134,666	32	325,910
25027	115.3	6987	805,671	32	3691
25030	832.7	6988	5,818,558	32	26,651
25033	4990.2	6989	34,876,298	32	159,720
25039		6990	-	32	-
25042	156.2	6991	1,092,204	32	5000
25045	2249.1	6992	15,725,987	32	71,988

Code district/ code commune	Mixed bamboo forest (ha)	N_{culm} ha^{-1}	N_{culm} (mil. culm)	AGC of bamboo plant ha^{-1} (tonne)	TC (tonne)
25048	3922.3	6993	27,428,364	32	125,540
25051	1881.6	6994	13,159,980	32	60,225
District 680	**18,908.1**	**6995**	**132,262,439**	**32**	**605,193**
25054	342.3	6996	2,395,011	32	10,957
25057	3850.8	6997	26,943,978	32	123,252
25060	4566.3	6998	31,954,967	32	146,154
25063	3406.8	6999	23,844,333	32	109,042
25066	4963.3	7000	34,743,310	32	158,861
25078	1106.9	7001	7,749,127	32	35,427
25090	329.5	7002	2,307,439	32	10,548
25093	342.2	7003	2,396,146	32	10,952
District 681	**9123.4**	**7004**	**63,900,154**	**32**	**292,012**
25096	926.8	7005	6,492,514	32	29,665
25099	209.0	7006	1,464,534	32	6691
25102	2040.5	7007	14,297,573	32	65,309
25105	514.1	7008	3,603,093	32	16,456
25108	766.0	7009	5,368,544	32	24,516
25111	43.0	7010	301,220	32	1375
25114	2344.1	7011	16,434,345	32	75,027
25117	125.9	7012	882,741	32	4029
25120	176.9	7013	1,240,670	32	5662
25123	1977.1	7014	13,867,309	32	63,281
District 682	**12,552.1**	**7015**	**88,053,192**	**32**	**401,756**
25126		7016	-	32	-
25129	1908.4	7017	13,391,102	32	61,082
25132	2133.4	7018	14,971,920	32	68,282
25135	2821.6	7019	19,804,530	32	90,310
25138	2043.3	7020	14,343,826	32	65,399
25141	636.2	7021	4,466,620	32	20,362
25144	327.8	7022	2,301,741	32	10,492
25147	660.0	7023	4,635,040	32	21,124
25153	192.1	7024	1,348,959	32	6147
25156	1829.6	7025	12,852,589	32	58,558
District 683	**4769.3**	**7026**	**33,508,751**	**32**	**152,649**
25159		7027	-	32	-
25162	611.9	7028	4,300,222	32	19,584
25165	2834.3	7029	19,922,576	32	90,719
25168	57.6	7030	404,928	32	1844
25171	24.7	7031	173,666	32	791
25174		7032	-	32	-
25177		7033	-	32	-
25180		7034	-	32	-
25183		7035	-	32	-
25189	29.2	7036	205,240	32	934
25192	1211.6	7037	8,525,818	32	38,779
Grand total	87,717.7	7038	617,357,032	32	2,807,580

Note: *In this case, TC stock only includes the AGC of bamboo plant.*

5.2. Report on emissions or removals of CO_2 of bamboo forest

There are two different, albeit equally valid, approaches to estimating carbon stock changes in the IPCC framework (IPCC, 2006): (a) the stock-based or stock difference approach and (b) the process-based or gain-loss approach.

1) *The stock-based or stock difference approach* estimates the difference in carbon stocks in a pool at two intervals according to the following formula:

$$\Delta C = \frac{C_{t_2} - C_{t_1}}{t_2 - t_1} \quad (54)$$

where ΔC is the annual carbon stock change in pool (t C year^{-1}); C_{t1} is the carbon stock in pool at time t_1 (t C) or, for all pools, it is TC_{t1} (t C); and C_{t2} is the carbon stock in pool at time t_2 (t C) or, for all pools, it is TC_{t2} (t C).

This method can be used when carbon stocks in relevant pools have been measured and estimated over time (e.g. in national forest inventories).

The equation (54) works well only if C_{t1} and C_{t2} have been measured on the same surface; in case of any change in the surface, an appropriate formulation is $\Delta C = \frac{C_2 - C_1}{t_2 - t_1} \times A_{t_2}$ where C_2 and C_1 are per hectare C stocks and A_{t2} is the bamboo forest area at time t_2.

2) *The process-based or gain-loss approach* estimates the net balance of additions to and removals from a carbon pool according to the following formula:

$$\Delta C = \Delta C_G - \Delta C_L \quad (55)$$

where ΔC is the annual carbon stock change in pool (t C year^{-1}), ΔC_G is the annual gain in carbon from rates of growth (t C year^{-1}), and ΔC_L is the annual loss of carbon (e.g. from harvest) (t C year^{-1}).

Both methods support reporting forest CO_2 equivalent emissions or removals at two intervals. However, the gain-loss method requires precise data on growth rates to determine 'gain', which requires the long-term observation of permanent plot systems, and it must have a good storage of forest harvesting data to determine 'loss'. There is limited information on the results of growth rates studies on bamboo forests for species and in different sites. Thus, this approach applies well to a country or territory that has effective forest management and a research system.

Meanwhile, the stock difference method can be comfortably used by simply collecting data on carbon stocks in either a pool or all the pools (the choice of pool depends on the conditions and resources of each country) by the National Forest Inventory. In this case, using the temporary random sample plots system for each forest carbon inventory yields more objective results than does the permanent sample plots system; this is due to unusual forest management, where forest owners avoid harvesting forest products intentionally in the permanent plots, which causes a bias of emissions/removals reports. As the methods and measurement approaches introduced in this manual suggest, the stock difference can be accordingly applied to estimate the difference in carbon stocks and changes.

6. QA and QC for data analysis

To ensure QA and QC, a short training course should be performed titled 'Field measurement and data analysis to report on bamboo forest carbon stock changes'. The curriculum framework is included in Annex 5: 'Training Short Course Curriculum – Module 2'. QA and QC should proceed with the steps and contents of the process of data analysis. Below are the recommendations for QA and QC, which should be performed step by step.

i) QA and QC for laboratory works

The volume of samples for identifying fresh-to-dry biomass encompasses a carbon forest inventory and its diverse types (bamboo, non-bamboo or litter) and bamboo components (culm, branches, leaves, rhizomes, roots, etc.) from multiple sample plots. Therefore, inappropriate arrangements may lead to the loss of and confusion about samples during transportation and processing in the laboratory. Thus, each sample is required to bear a code associated with the plot, bamboo plant and bamboo plant components and should be monitored during transport in the handling stages.

Weighing the samples precisely is an important requirement in the laboratory. The use of electronic calipers with precision 0.1 mg and mass weights should be performed at least twice per sample by two different staff members. Where possible, 10-20 per cent of the samples should be reanalysed for errors in estimates (Pearson, Brown and Birdsey, 2007; Petrova et al, 2010; Subedi et al, 2010).

ii) QA and QC for data entry

To assure data reliability, the appropriate entry of data into data sheets is vital. The following points illustrate the key issues that need to be considered to minimise errors (Petrova et al, 2010; Subedi et al, 2010; Pearson, Brown and Birdsey, 2007):

- Units used in the field measurement and the data entry must be consistent.
- All data sheets and forms used either in the field or in the room should include a field called 'Recorded/Analysed by'. Communication between staff who carry out field measurements and data analyses is useful to address any potential problems.
- To avoid entering data and formulas incorrectly, data entry results should be checked independently by other people.
- Errors can be reduced if the entered data are reviewed through comparison with the independent data and cross-checks by independent staff.
- Outliers can be discovered by checking whether each value is within an expected range. If there are anomalies that cannot be addressed, the erroneous data, sample or plot should not be factored in the final data analysis.

iii) QA and QC for data archiving

Owing to the relatively long-term nature of forestry activities, data storage and maintenance are important. Data must be stored in several forms and copies of all data should be shared with all the authorised personnel (Pearson, Brown and Birdsey, 2007).

Here are some forms of data storage:

- The original data from the field and the laboratory need to have at least two copies and be stored in a safe place.
- The original data files, intermediate processing data, resulting files, RS and GIS files should be stored on a common computer, separate hard disk and on the computer of some of the respective individuals.
- It is highly recommended that data files be stored in the cloud (e.g. Dropbox, OneDrive).

ANNEXES

Annex 1: A data set of *Bambusa procera* for developing and validating bamboo allometric equations

ID	Plot_ Code	X	Y	Plant_ Code	D	H	A	Bfcu	Bfbr	Bfle	AGBf	RatioBcu	RatioBbr	RatioBle	Bcu	Bbr	Ble	AGB
1	L1	755687	1352820	L1.1	8.6	21.6	1	23.7	6.6	2.4	32.7	0.57	0.404	0.457	13.51	2.68	1.08	17.27
2	L1	755687	1352820	L1.2	7.4	11.9	5	19.7	5.5	2	27.2	0.547	0.469	0.45	10.78	2.59	0.89	14.25
3	L1	755687	1352820	L1.3	6.4	14.1	2	13.5	3.8	1.4	18.6	0.459	0.46	0.48	6.2	1.74	0.65	8.58
4	L1	755687	1352820	L1.4	7.1	14.1	4	20.4	5.7	1.9	28	0.575	0.472	0.491	11.73	2.7	0.91	15.33
5	L1	755687	1352820	L1.5	6.5	12.2	3	18.3	4.7	1.8	24.8	0.439	0.426	0.504	8.03	2	0.92	10.96
6	L10	759500	1342188	L10.1	5.1	10.3	1	7.6	4	1.6	13.2	0.551	0.499	0.511	4.19	2.01	0.8	6.99
7	L10	759500	1342188	L10.2	4.3	16.9	2	10	3.9	0.5	14.4	0.548	0.499	0.347	5.48	1.95	0.17	7.6
8	L10	759500	1342188	L10.3	4.1	6.5	3	3.7	3.9	1.5	9.1	0.534	0.48	0.45	1.97	1.87	0.68	4.52
9	L10	759500	1342188	L10.4	4.7	7.5	4	6.8	3.6	1.4	11.8	0.682	0.507	0.488	4.64	1.82	0.68	7.14
10	L10	759500	1342188	L10.5	4.2	6.1	5	4.1	1.6	0.5	6.2	0.578	0.672	0.536	2.37	1.08	0.26	3.71
11	L11	765333	1342076	L11.1	4.5	9.9	1	5.5	0.3	0.5	6.2	0.497	0.499	0.511	2.73	0.13	0.23	3.1
12	L11	765333	1342076	L11.2	5.2	13.3	2	10	4.6	1.2	15.8	0.491	0.499	0.511	4.91	2.28	0.61	7.8
13	L11	765333	1342076	L11.3	4.6	8.7	3	6.1	0.3	0.5	6.9	0.598	0.552	0.496	3.65	0.17	0.25	4.06
14	L11	765333	1342076	L11.4	4	6.7	4	4.3	1.3	0.5	6.1	0.56	0.601	0.442	2.41	0.78	0.23	3.42
15	L11	765333	1342076	L11.5	4.9	7.2	5	5.7	2.6	0.7	9	0.634	0.651	0.557	3.62	1.69	0.38	5.69
16	L12	180045	1363325	L12. 1	5.1	18.9	1	11.6	3.2	1	15.9	0.516	0.499	0.511	5.98	1.62	0.51	8.12
17	L12	180045	1363325	L12. 2	6.9	17.2	2	20.8	5.8	1.8	28.4	0.627	0.468	0.562	13.05	2.73	1.01	16.79
18	L12	180045	1363325	L12. 3	5.8	13.9	3	11	3.1	0.8	14.9	0.511	0.474	0.523	5.62	1.46	0.42	7.5
19	L12	180045	1363325	L12. 4	6.1	13.2	4	15.4	4.3	1.5	21.3	0.704	0.499	0.591	10.84	2.15	0.91	13.9
20	L12	180045	1363325	L12. 5	6.3	15	5	14.6	4.1	1.2	19.9	0.597	0.591	0.589	8.72	2.42	0.71	11.85
21	L13	180292	1363227	L 13. 1	5.7	19.6	1	15	5	1.5	21.5	0.415	0.499	0.511	6.23	2.47	0.77	9.46
22	L13	180292	1363227	L 13. 2	6.1	17.1	2	15	5	1.5	21.5	0.446	0.499	0.51	6.69	2.47	0.77	9.92
23	L13	180292	1363227	L 13. 3	6.3	16	3	15	3.5	1.4	19.9	0.53	0.621	0.536	7.94	2.17	0.75	10.87
24	L13	180292	1363227	L 13. 4	6.1	11.1	4	10.1	7.5	1	18.6	0.675	0.396	0.544	6.82	2.97	0.55	10.34
25	L13	180292	1363227	L 13. 5	5.6	10.8	5	9.5	7	0.7	17.2	0.651	0.541	0.571	6.19	3.79	0.4	10.38

ID	Plot_ Code	X	Y	Plant_ Code	D	H	A	Bfcu	Bfbr	Bfle	AGBf	RatioBcu	RatioBbr	RatioBle	Bcu	Bbr	Ble	AGB
26	L14	180395	1363148	L 14. 1	7.6	13.1	1	14.1	3.9	1.4	19.5	0.49	0.499	0.511	6.91	1.97	0.72	9.6
27	L14	180395	1363148	L 14. 2	7.2	12.1	2	14.5	4.1	1.7	20.3	0.629	0.48	0.577	9.12	1.95	1	12.07
28	L14	180395	1363148	L 14. 3	7.3	15.1	3	16.9	4.7	2	23.7	0.597	0.529	0.551	10.1	2.5	1.12	13.72
29	L14	180395	1363148	L 14. 4	5.4	12.1	4	7.1	2	1.1	10.2	0.543	0.44	0.527	3.85	0.87	0.58	5.31
30	L14	180395	1363148	L 14. 5	8.1	13.6	5	16.4	4.6	2	23	0.439	0.685	0.513	7.19	3.14	1.03	11.36
31	L15	182804	1359934	L 15. 1	6.7	25.4	1	25	7.5	2.5	35	0.659	0.499	0.511	16.47	3.74	1.28	21.49
32	L15	182804	1359934	L 15. 2	6.9	22	2	12.6	3.8	1.6	18	0.452	0.5	0.556	5.69	1.89	0.89	8.47
33	L15	182804	1359934	L 15. 3	5.8	22	3	12	3.6	1.5	17.1	0.536	0.498	0.594	6.44	1.79	0.89	9.12
34	L15	182804	1359934	L 15. 4	6.3	22.6	4	11	3.3	0.8	15.1	0.521	0.498	0.601	5.73	1.64	0.48	7.85
35	L15	182804	1359934	L 15. 5	5.5	19.5	5	10.2	3.1	0.7	14	0.611	0.497	0.58	6.23	1.52	0.41	8.16
36	L16	182974	1359827	L 16.1	7.4	16.5	1	12.2	5.6	1.5	19.2	0.507	0.497	0.511	6.18	2.76	0.75	9.69
37	L16	182974	1359827	L 16.2	4.6	15.2	2	7.4	3.4	0.1	10.9	0.289	0.498	0.287	2.14	1.68	0.04	3.86
38	L16	182974	1359827	L 16.3	6.6	18.1	3	10.5	4.8	2.1	17.4	0.635	0.499	0.649	6.67	2.38	1.36	10.42
39	L16	182974	1359827	L 16.4	5.8	16	4	15.6	7.1	1.9	24.6	0.668	0.516	0.525	10.42	3.66	0.98	15.06
40	L16	182974	1359827	L 16.5	6.2	13.9	5	15.2	4.3	1.8	21.3	0.624	0.586	0.537	9.48	2.49	0.98	12.95
41	L17	183035	1359706	L 17.1	4.6	13.8	1	4.1	0.7	0.6	5.5	0.519	0.499	0.511	2.13	0.37	0.32	2.82
42	L17	183035	1359706	L 17.2	5.3	18	2	6.4	1.1	1.6	9.1	0.556	0.498	0.536	3.56	0.57	0.86	4.99
43	L17	183035	1359706	L 17.3	5.7	14.3	3	8.2	1.5	1.4	11.1	0.586	0.5	0.559	4.81	0.74	0.78	6.32
44	L17	183035	1359706	L 17.4	4.7	12.6	4	7.8	1.4	1.2	10.4	0.539	0.52	0.536	4.2	0.73	0.64	5.57
45	L17	183035	1359706	L 17.5	4.6	18.5	5	8.6	1.5	1	11.2	0.51	0.5	0.59	4.39	0.77	0.61	5.77
46	L2	755570	1352731	L2.1	6.5	17	2	17.3	4.8	1.7	23.9	0.479	0.49	0.457	8.29	2.37	0.79	11.45
47	L2	755570	1352731	L2.2	6.3	17.1	1	17.4	4.9	1.7	24	0.508	0.44	0.456	8.84	2.14	0.79	11.78
48	L2	755570	1352731	L2.3	7	12.3	3	17.7	4.2	1.8	23.7	0.566	0.336	0.504	10.02	1.41	0.89	12.32
49	L2	755570	1352731	L2.4	8.3	16	5	35.9	7.7	2.9	46.5	0.657	0.599	0.508	23.59	4.61	1.47	29.67
50	L3	757865	1355564	L3.1	4.8	11.2	1	5.5	0.7	0.4	6.6	0.492	0.305	0.477	2.71	0.21	0.19	3.11
51	L3	757865	1355564	L3.2	6.9	16.3	2	11.8	3.3	1.2	16.3	0.413	0.406	0.367	4.87	1.34	0.43	6.65
52	L3	757865	1355564	L3.3	4.5	11.5	4	6.1	3.4	0.7	10.2	0.507	0.373	0.406	3.09	1.27	0.28	4.65
53	L3	757865	1355564	L3.4	3.6	11.8	3	4.5	0.8	0.8	6.1	0.45	0.38	0.399	2.03	0.3	0.32	2.65
54	L4	755264	1354088	L4.1	7.4	16.6	2	20.8	5.8	2.1	28.7	0.493	0.385	0.458	10.25	2.24	0.95	13.45
55	L4	755264	1354088	L4.2	5.6	17.4	1	18.7	3.6	0.5	22.7	0.549	0.44	0.458	10.27	1.57	0.22	12.06

ID	Plot_ Code	X	Y	Plant_ Code	D	H	A	Bfcu	Bfbr	Bfle	AGBf	RatioBcu	RatioBbr	RatioBle	Bcu	Bbr	Ble	AGB
56	L4	755264	1354088	L4.3	5.6	13.8	4	9.7	1.9	0.3	11.8	0.618	0.561	0.489	5.99	1.04	0.12	7.15
57	L4	755264	1354088	L4.4	6.7	9.2	5	12.5	4.9	1.3	18.7	0.649	0.539	0.502	8.11	2.64	0.63	11.38
58	L4	755264	1354088	L4.5	9.5	16.4	3	26.7	7.5	2.7	36.8	0.588	0.493	0.459	15.7	3.69	1.23	20.61
59	L5	755310	1353994	L5.1	4.7	14.9	2	13.1	0.6	1.3	15	0.515	0.292	0.457	6.75	0.18	0.6	7.52
60	L5	755310	1353994	L5.2	6.8	17.1	1	15.3	5.7	1.3	22.3	0.483	0.44	0.456	7.39	2.52	0.59	10.49
61	L5	755310	1353994	L5.3	6.9	12.1	4	13.1	4.9	1.1	19.1	0.56	0.461	0.522	7.34	2.26	0.57	10.17
62	L5	755310	1353994	L5.4	7.3	13.3	5	17.7	8.9	1.8	28.4	0.463	0.411	0.402	8.2	3.66	0.71	12.56
63	L5	755310	1353994	L5.5	7.4	12.8	3	19	6.6	1.2	26.8	0.633	0.542	0.357	12.03	3.58	0.43	16.03
64	L6	748987	1361093	L6.1	7.8	21.2	1	32.4	9.1	2.4	43.9	0.657	0.499	0.511	21.27	4.53	1.22	27.02
65	L6	748987	1361093	L6.2	5.6	11.7	2	16.2	4.5	1.6	22.4	0.481	0.499	0.511	7.79	2.26	0.83	10.88
66	L6	748987	1361093	L6.3	6.5	13.6	3	14.5	3.2	1.5	19.2	0.794	0.69	0.678	11.51	2.21	1.02	14.73
67	L6	748987	1361093	L6.4	6.8	13	4	19.5	5.5	2	26.9	0.548	0.568	0.546	10.68	3.1	1.07	14.84
68	L6	748987	1361093	L6.5	8.7	17.6	5	41.9	11.7	3.1	56.7	0.624	0.467	0.618	26.13	5.48	1.92	33.53
69	L7	763190	1344394	L7.1	5.5	14.2	1	6.6	2	1.9	10.5	0.759	0.4	0.511	5.01	0.79	0.96	6.77
70	L7	763190	1344394	L7.2	5.6	15.3	2	6.3	1.9	1.8	10	0.631	0.652	0.511	3.98	1.23	0.92	6.13
71	L7	763190	1344394	L7.3	4.6	6.9	3	2.9	0.9	0.7	4.5	0.695	0.499	0.484	2.01	0.43	0.34	2.79
72	L7	763190	1344394	L7.4	5.5	13.6	4	6.5	2	2.3	10.8	0.544	0.499	0.517	3.54	0.97	1.19	5.7
73	L7	763190	1344394	L7.5	5.5	10.5	5	5	1.5	0.2	6.7	0.437	0.498	0.483	2.18	0.75	0.1	3.03
74	L8	759500	1342188	L8.1	8.2	19.5	1	34.4	9.6	2.4	46.5	0.524	0.5	0.511	18.03	4.82	1.25	24.1
75	L8	759500	1342188	L8.2	5.3	15.7	2	10.6	2.6	0.9	14.1	0.647	0.498	0.51	6.86	1.29	0.43	8.59
76	L8	759500	1342188	L8.3	7.3	19.2	3	26.7	3.9	1.9	32.5	0.525	0.475	0.605	14.02	1.85	1.15	17.02
77	L8	759500	1342188	L8.4	7.8	12.7	4	21	4.9	2.1	28	0.586	0.589	0.515	12.3	2.89	1.08	16.26
78	L8	759500	1342188	L8.5	8.1	14.3	5	26.1	6.4	2.1	34.6	0.445	0.541	0.64	11.61	3.46	1.34	16.41
79	L9	759613	1342238	L9.1	9.2	19.2	1	30.3	8.5	3	41.8	0.579	0.499	0.511	17.55	4.23	1.53	23.32
80	L9	759613	1342238	L9.2	7	18.4	2	19	5.3	1.5	25.9	0.395	0.499	0.511	7.5	2.65	0.78	10.94
81	L9	759613	1342238	L9.3	6.2	11.4	3	7.1	2	1.4	10.5	0.479	0.388	0.562	3.4	0.77	0.79	4.96
82	L9	759613	1342238	L9.4	7.7	15.6	4	22.3	6.2	1.8	30.3	0.327	0.56	0.539	7.29	3.5	0.97	11.76
83	L9	759613	1342238	L9.5	6.2	10.4	5	10.1	6	1.9	18	0.564	0.59	0.541	5.69	3.54	1.03	10.26

Note: *D, H* and *A are diameters at breast height in cm, height in mm and age in year, respectively; Bfcu, Bfbr, Bfle and AGBf are fresh biomass of bamboo plant culms, branches, leaves and total in kg, respectively; $RatioB_{cu}$, $RatioB_{br}$ and $RatioB_{le}$ are fresh-to-dry mass ratios of culms, branches and leaves, respectively; B_{cu}, B_{br}, B_{le} and AGB are dry biomass of culms, branches, leaves and total in kg, respectively.*

Annex 2. Materials, tools and equipment needed for field measurement for bamboo forest carbon assessment

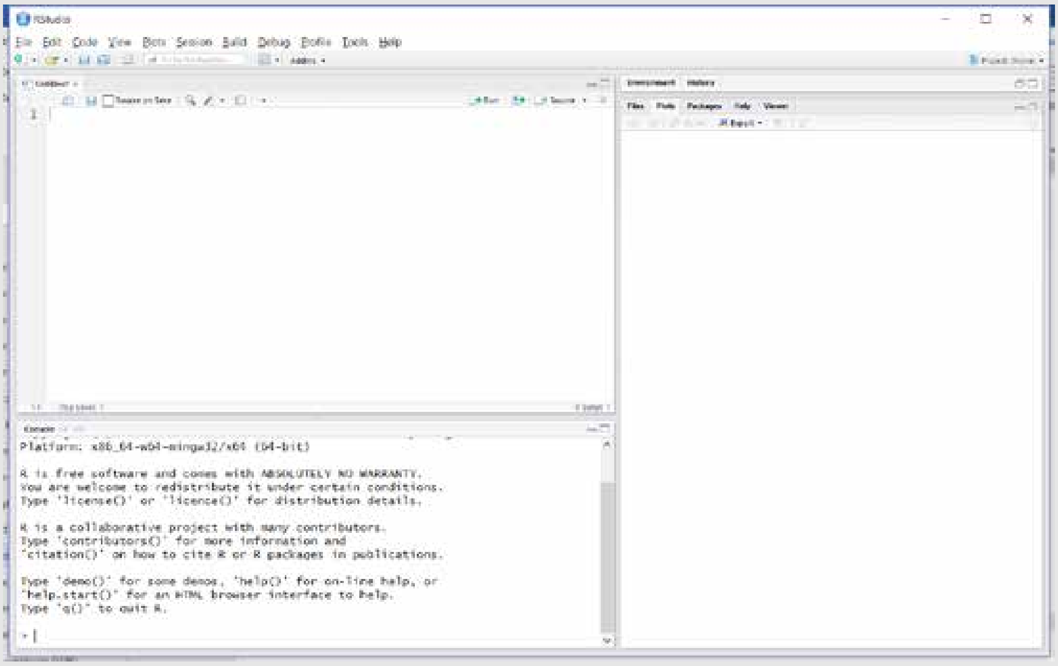
No	Item	Purpose
1.	Forest stratification map	Check forest status in the field
2.	Map of sample plots location	Determine sample plot
3.	Sheets for field measurement	Record field data
4.	GPS and battery	Determine random sample plot
5.	Knotted ropes	Establish plots
6.	4 frames of 70.7 × 70.7 cm	Establish subplots for non-bamboo and litter measurement
7.	LaserAce	Measure distance for circular plots, the plant height
8.	DME	Measure distance for circular plots
9.	Sunnto clinometer	Measure compass and height
10.	Diameter measurement tape (D-Tape)	Measure diameter at breast height
11.	Electronic calliper and battery	Diameter measurement for small bamboo
12.	Measuring tape (30 m)	Measuring girth of bamboo clump, distance between clumps
13.	Soil core	Take fine root
14.	Hand saw	Cut bamboo culm for samples
15.	Knife	Separate bamboo components
16.	Scissors	Harvest non-bamboo vegetation
17.	Scale	Weigh fresh biomass of bamboo components: culm, branches and leaves, litter, non-bamboo plant, rhizomes, coarse roots
18.	Precision electronic scale to 0.1 g	Weigh biomass samples
19.	Hoe	Dig soil pit
20.	Name tag	Code the samples
21.	Nylon bag	Keep samples
22.	Coloured pen	Mark bamboo
23.	Digital camera	Take pictures of plots, samples

Annex 3. Setting up open source software R and running R code

Box 18. Set up open source software R and run R code provided in this guideline

1. *Set up R software*
   - Download R for Windows at https://cran.r-project.org/bin/windows/base/ and then install it.
   - Download R Studio at https://www.rstudio.com/products/rstudio/download/ and then install it.

Below is the R Studio Window running after installation.



2. *Prepare data file used for R*
   Enter the dataset for developing and validating models into an Excel sheet that contains columns of variables and save as file type of *.txt that would run in R software (see an example a data file for R in Annex 1.)

3. *Run R codes*
   - Click on R App. icon to run R Studio
   - Write R codes yourself or copy given R codes in the Boxes of this manual and paste them into the left-top window of R Studio.

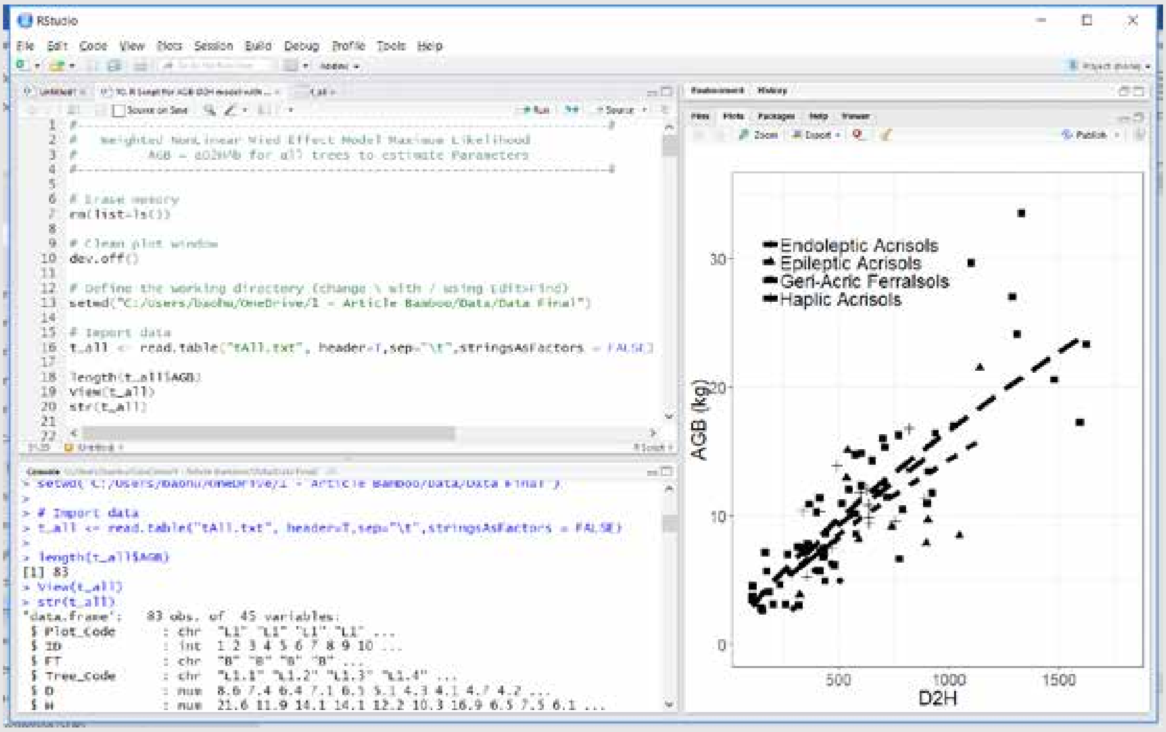
   - Define your working directory in a line of R code thus: (in "….."):
     setwd("C:/Users/baohu/OneDrive/1 - Bamboo INBAR/R code and Data")

   - Provide file name (file type: *.txt) that contains your data set in a line of R code (e.g. tAll.txt):
     t <- read.table("tAll.txt", header=T,sep="\t", stringsAsFactors = FALSE)
     For the data file running in R, you can enter your data in Excel and then save the file as *.txt

- Click ‘Run’ to run the whole R codes
- To run the current line or a selection of R code: press Ctrl + Enter

4. *Results by running R codes*
   - The results of calculation based on R codes appear in the left-below window of R Studio.
   - The plots (if applicable) show in the right window of R Studio.

   Results of steps 3 and 4 are shown in the windows of R Studio below.



Annex 4. Training Short Course Curriculum – Module 1

Title: Methodology of carbon estimation for bamboo forest and development and cross-validation of allometric equation

Target trainee: Technical staff, researchers and lecturers who graduated from the university/college of forestry, environment, natural resources management and other fields related to the forest.

Objectives of the training: By the end of the training, the trainee will be able to

- provide an overview of carbon estimation methodology in bamboo forest pools, and
- develop and cross-validate allometric equations for estimating biomass and carbon in bamboo forests.

Duration: Three days; two days for theory and one day for practice in a bamboo forest
Curriculum framework:

Day/time	Topic	Teaching/learning method	Materials, equipment
Day 1 9:00-12:00	Methodology of carbon estimation in four carbon pools of bamboo forest	Presentation Question and answer (Q/A) Plenary discussion	Projector
13:30-18:00	Data collection and measurement of variables for different allometric equations	Presentation Q/A	Projector
Day 2 9:00-17:00	Idem	Practice in bamboo forest in small groups (five people)	Materials and equipment for data collection in the field (see Annex 2)
Day 3 9:00-18:00	Development and cross-validation of allometric equations using R statistical software	Computer demonstration using R Small groups/individuals working on computers with R	Individual laptops

Annex 5. Training Short Course Curriculum - Module 2

Title: Field measurement and data analysis to report on bamboo forest carbon stock changes

Target trainee: Technical staff who graduated from the university/college of forestry, environment, natural resources management and other fields related to the forest.

Objectives of the training: By the end of the training, the trainee will be able to

- design sampling for data collection for bamboo biomass estimation;
- carry out a sample plot measurement;
- work in the laboratory to determine the fresh-to-dry mass ratio;
- calculate and estimate bamboo stock, biomass and carbon sequestration in bamboo forest pools; and
- report on bamboo stock, emissions or removals of CO_2 of bamboo forest.

Duration: Four days; three days in the room and one day practising in the bamboo forest

Curriculum framework:

Day/time	Topic	Teaching/learning method	Materials, equipment
Day 1 9:00-10:00	Overview of requirements for field data collection for bamboo biomass carbon estimates	Presentation Q/A	Projector
10:00-18:00	Sampling design: plot shape, plot size, sample size, plot layout	Presentation Plenary discussion	Projector
Day 2 9:00-11:00	Design random sample plots in GIS map and upload to GPS	Demonstration of GIS software Q/A	Individual laptops Installed ArcGIS or qGIS
11:00-18:00	Sample plot measurement: determine sample plots in the field using GPS, establish sample plots, measure variables within sample plots and taking samples	Demonstration of using materials, equipment Q/A	Materials, equipment (see Annex 2)
Day 3 8:00-17:00	Idem	Practice in the bamboo forest in small groups (five people)	Materials, equipment (see Annex 2)
Day 4 9:00-10:00	Laboratory work to determine the fresh-to-dry mass ratios	Demonstration of using oven-dryer machine Practice in small groups Q/A	Dryer machines
10:00-12:00	Calculation and estimation of bamboo stock, biomass, carbon sequestration in bamboo forest pools	Demonstration on computers Practice in small groups Q/A	Individual laptops
13:00-18:00	Report on bamboo stock, emissions or removals of CO_2 of bamboo forest	Demonstration on computer Practice in small groups Q/A	Individual laptops

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