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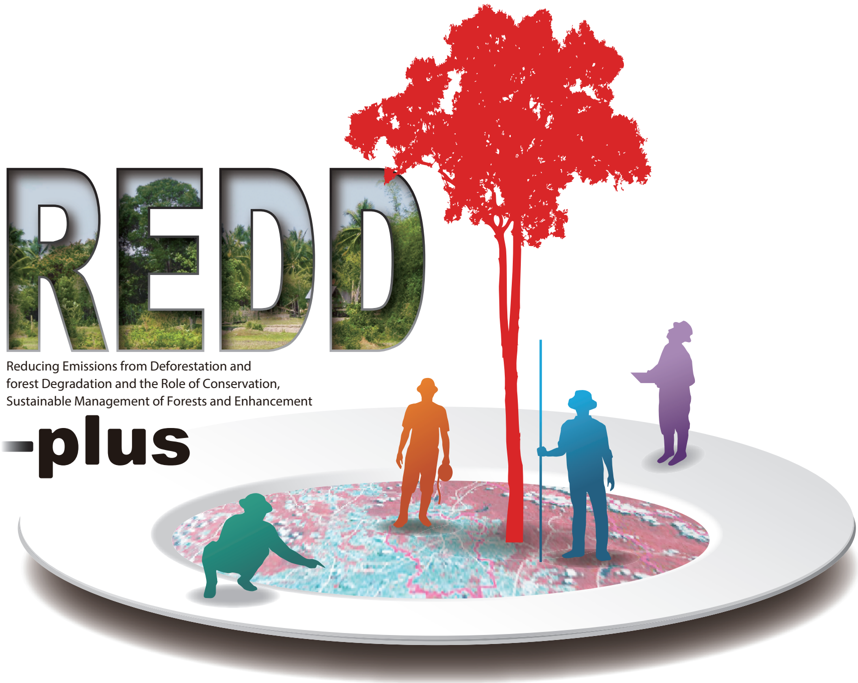

COOKBOOK ANNEX

Research Manual Vol. 1
Ground-Based Inventory

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Research achievement of the 4th mid-term plan 1 (Forest Management Technology-1)

Preface

The basic concept of REDD-plus is to provide economic incentives such as funding and credits to developing countries for REDD activities (reducing emissions from deforestation and forest degradation) and “plus” activities (reducing CO_2 emissions and CO_2 levels in the atmosphere by carbon sequestration). Thus, in order to estimate the changes in the amount of carbon stored in forests, monitoring using a scientific approach is essential.

The REDD Research and Development Center, Forestry and Forest Products Research Institute, compiled “REDD-plus Cookbook” in 2012, an easy-to-understand technical manual that provides basic knowledge and techniques required for REDD-plus, with the primary focus on forest carbon monitoring methods. Knowledge and techniques required for REDD-plus are compiled in units termed as “Recipe” in this REDD-plus Cookbook. This REDD-plus Cookbook is intended for the policy makers working for the introduction of REDD-plus and the practitioners and experts working on REDD-plus activities.

As REDD-plus Cookbook focuses on basic knowledge and techniques required for REDD-plus, the experts working on REDD-plus activities will need further detailed information in the field. Thus, we compiled “REDD-plus Cookbook Annex” to provide the experts with more detailed and practical information in each “Recipe”. In this manual, specific measuring methods are explained. In addition, this manual is intended to be used as a textbook for capacity building. In order to have a better technological understanding on these topics, it is recommended to read this manual in conjunction with REDD-plus Cookbook.

We hope this manual will contribute to the promotion of REDD-plus in several parts of the world.

September, 2016

The REDD Research and Development Center
Forestry and Forest Products Research Institute

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1 Outline

1.1 Purpose of REDD-plus Cookbook Annex

REDD-plus Cookbook compiled in 2012 is an easy-to-understand technical manual that provides basic knowledge and techniques required for REDD-plus, with the primary focus on forest carbon monitoring methods. REDD-plus Cookbook explains the estimation method of forest carbon stocks, while this manual explains, inter alia, inventory methods focusing on the ground-based inventory needed to develop equations for estimating carbon stocks per unit area.

This manual is intended for experts who will actually collect data on forest carbon stocks. We hope this manual will also be useful for students studying forestry and forest ecology, NGOs interested in REDD-plus, and people concerned in this field.

1.2 How to use this manual

A ground-based inventory is carried out by establishing a number of plots; therefore, accurate measurement of plots is of critical importance. In particular, when the inventory is carried out by more than one team simultaneously, the inventory method should be carefully checked in advance. It is advisable to know the inventory process from this manual before planning a ground-based inventory.

In this manual, Chapter 2 explains how to establish plots for the ground-based inventory, Chapter 3 explains the specific inventory procedure, and Chapter 4 explains the specific calculation methods of the carbon stocks per unit area from the inventory data obtained in the field.

Please see TIPS as for the points to consider in the field.

1.3 Recipes covered by REDD-plus Cookbook

Recipes covered by REDD-plus Cookbook are shown in [ ]. Please refer to REDD-plus Cookbook.

REDD-plus Cookbook can be downloaded from the Website mentioned below.

http://redd.ffpri.affrc.go.jp/index_en.html

2 Methods for establishing sample plots

2.1 Purpose of establishing sample plots

In the 2006 IPCC guidelines, two methods of calculating changes in carbon stocks (forest biomass) are presented: the gain-loss method and the stock change method. The gain-loss method calculates carbon stock changes by taking the difference between increases and decreases in emissions, whereas in the stock change method the change in carbon stocks (which reflect emissions and removals) is determined from the difference in carbon stocks measured at different time points [***Recipe-P04, P07***].

The gain-loss method requires accurate data on carbon stocks lost by logging and forest disturbances, which is often difficult to obtain. For this reason, the stock change method, in which the difference in carbon stocks at two different time points is presumed to equal the emissions and removals during that time interval, is more widely applicable [***Recipe-P07***]. At the national level, remote sensing and ground-based inventory used in combination can effectively determine carbon stock changes.

The estimation of the amount of carbon stocks per unit area is done by two methods: a method that directly measures the amount of carbon in the forest and a method that indirectly measures the amount of carbon stocks using the estimation model [***Recipe-P09***]. Each method has advantages and disadvantages and is applicable under different conditions. A ground-based inventory using permanent sample plots has the advantage that it can be used to detect land-use changes, such as conversion to farmland and selective logging, and to monitor forest carbon stocks in a large area over time [***Recipe-P09***]. For national-level measurement, however, several permanent sample plots are needed [***Recipe-P10***]. In this manual, methods for establishing and measuring the sample plots, which are considered to be the most technically feasible for the ground-based inventory, are explained.

This manual focuses on four carbon pools, except for soil (above-ground biomass, belowground biomass, leaf litter layer, and dead wood).

2.2 Design of inventory

2.2.1 Auxiliary data

To calculate forest carbon stocks per unit area, a large number of permanent sample plots need to be established; however, when the National Forest Inventory (NFI) [***Recipe-T01***] has been carried out in the target country, the number of plots required for high-accurate data can be determined based on NFI [***Recipe-T12***]. Moreover, it is necessary to collect case studies on forest carbon stocks carried out in the target country and to know whether allometric equations required for calculating biomass have been developed [*Recipe-T03*]. In the absence of sufficient information, data on neighboring countries and regions are used.

2.2.2 Establishment of sample plots

To prevent permanent sample plots from being concentrated in readily accessible locations such as near roads or villages, permanent sample plots should be established using either a simple random sampling method or a systematic sampling method [*Recipe-P10, T12*]. Moreover, a stratified sampling method, in which the number of sampling sites and their locations by forest categories are decided in advance on the basis of remote sensing data, can improve sampling survey efficiency [*Recipe-T12*].

An effective means of stratification is to create a stratification matrix (Figure 1). This matrix is constructed with two axes: one axis shows forest types and other shows the state or condition of the forest (the degree of forest degradation or the succession stage) [*Recipe-T12*]

Forest type	<----------------------------- Forest conditions -------------------------------------- >			
Lowland forest	Mature	Selective logged	Secondary (medium age)	Secondary (young age)
Dry forest	Mature	Selective logged	Secondary (medium age)	Secondary (young age)
Plantation	Mature	Medium age		Young age

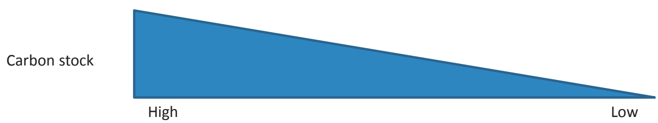


Figure 1 Example of stratification matrix

The horizontal axis shows the condition of the forest and the vertical axis shows forest types.

2.2.3 Required number of plots

Where a forest area is divided into L strata, the total required number (n) of permanent sample plots is obtained as follows:

$$n = \frac{\left[\sum_{i=1}^{L} N_i * S_i\right]^2}{\left(N * \frac{E}{t}\right)^2 + \sum_{i=1}^{L} N_i * (S_i)^2}$$

where *i* is the stratum, *L* is the number of stratum, *N* is the maximum number of plots in the target area (a value obtained by dividing the total target region by the sample plot area), *Ni* is the maximum number of plots in each stratum (the value obtained by dividing each stratum area by the sample plot area), *Si* is the standard deviation of each stratum, *E* is the permissible error in the estimated amount (e.g. 10% of the biomass average value), and *t* is a 5% significance level of the t-distribution. The cost for establishing plots is not taken into consideration in the above formula.

The total cost including the cost of establishing plots is calculated using a different formula, but there is no big difference in the necessary numerical information [***Recipe-T12***].

After calculating the required total number of plots using the above formula, the number of required plots for each stratum (*ni*) can be determined as follows:

$$n_i = n \times \frac{N_i \times S_i}{\sum_{i=1}^{L} N_i \times S_i}$$

2.3 Design of plot

2.3.1 Plot area

The larger the area of each permanent sample plot, the larger the number of trees that must be measured and the larger the time and expense required for the measurement. On the other hand, if the area of each sample plot is small, measurement requires relatively little time and expense, but the error in the carbon stock measurement result will increase [***Recipe-T13***]. Moreover, plot area should be chosen with reference to the national forest inventory, if one has been carried out in the past in the country, and after researching the forest structure and other characteristics of the forest. As a rough standard, an area of 0.1–0.5 ha is often used.

2.3.2 Plot shape

In general, sample plots (either circular or rectangular shape) are often used (Fig. 2). Each shape has advantages and disadvantages in setting up and use. For example, the location of the plot is marked with stakes. For a circular plot, a stake is established at the central point, but it may be difficult to know whether individual trees near the plot boundary are within the plot and the measurement object. On the other hand, a rectangular plot requires a stake in all four corners, but it is easy to determine whether the tree is a measuring target due to the straight lines of the plot. Moreover, the measurement is carried out repeatedly; therefore, a rectangular plot has the advantage that is easy to locate, even though four stakes need to be established at all four corners.

For accurate determination of the forest structure in a plot, all living trees within the plot should be measured; however, this is laborious with regard to time and effort. Time and effort can be saved using a nested plot structure (Figure 2, Gray area)[***Recipe-T13***].

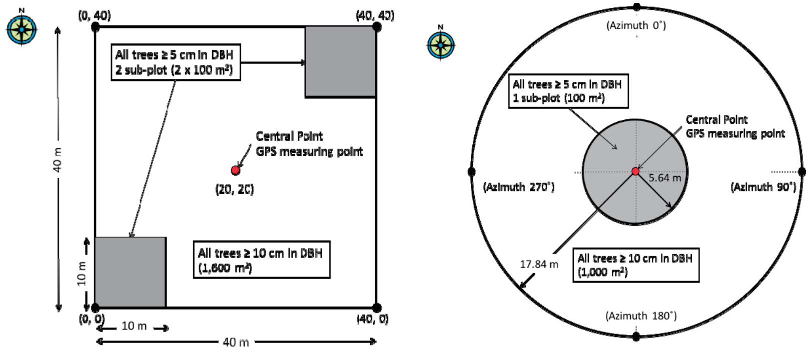


Figure 2 Shapes of sample plot

Left: Rectangular-shaped plot (0.16 ha), Right: Circular-shaped plot (0.1 ha)

2.4 Tools required for inventory

Tools required for establishing plots are shown in Table 1. The distance measurement in the forest is carried out efficiently using measurement tools such as a laser range finder or an ultrasonic range finder.

Table 1 Tools required for establishing plots

Tool	Number	Remarks
Laser range finder	1	For measuring horizontal distance
Tape measure (30 –50 m)	1-3	For measuring the slope distance using a tape measure when a laser range finder is not available.
Clinometer	1	For recording the inclination of the plot
Azimuth compass	1-2	For establishing plots and recording the plot location
GPS	1	For recording plot location
Stakes	>1	Material of stakes varies depending on plot location.
Digital camera	1	For recording forest type of plot

TIPS It should be noted that an ultrasonic range finder might be unavailable near the river or disturbed by the buzzing of cicadas and/or sound of a brook.

2.5 Members of the team

After deciding the point to be measured, the compartment of plot needs be determined. For this measurement, the staff shown in Table 2 are needed. The measurement will be carried out more efficiently with more than one team.

Table 2 Number of staff required for establishing plots

Role	Desired number of staff	Remarks
Staff who operate a laser range finder	1-2	For indicating orientation and distance to establish plots
Staff for data entry	1	For recording location, inclination, orientation, etc.
Assistant staff	2–4	For establishing stakes

2.6 Plot establishment in the field

2.6.1 Information to be recorded

A sample plot is classified into two types: a permanent sample plot (PSP) (for repeated measurements) and one-shot plot (for a one-time use). In both cases, the plot location measured using GPS should be recorded. There is a large amount of information to be recorded as shown in Table 3 when establishing the plot, but some of the information should be gathered in advance.

In addition, information about the forest where the sample plot is established should be recorded, including disturbance history and conditions of surrounding areas. The type of disturbance, including human-induced disturbance (logging, conversion to agricultural land, etc.) or natural disturbance (fire, meteorological damage, etc.), should be recorded in as much detail as possible. The degree and duration of the disturbance should also be recorded in as much detail as possible because these factors affect the forest carbon stocks.

2.6.2 Procedures for establishing a plot

Here, the specific procedure for establishing a plot is explained by taking a rectangular-shaped plot (40 m × 40 m) as an example.

First, select the candidate location for establishing a plot based on the predetermined location (the distance from the forest road, etc.). After selecting the candidate location, determine the location to establish the plot. Then, record the position measured by GPS. Here, the location is the center point of the plot (Figure 3a).

To create a nested plot structure in the plot, establish grid points at 10 m interval. From there, extend the survey lines to the north and south directions by 10 m, respectively, from the center point (a total of 20 m) (Figure 3b). After extended by 20 m, change the direction by 90 degrees and then extend the survey line to the north and south directions by 20 m, respectively. At the point where the survey line is extended by 20 m, establish a stake as a boundary point (Figure 3c). In order to establish a grid with a grid interval of 10 m, draw a survey line on the fishbone pattern along the central point (Figure 3d) and then make a sub-quadrat by extending the survey line toward the boundary point (Figure 3e). Here, the distance of grid interval is not the slope distance but the horizontal distance. Stakes established at the boundary point of the reference point and the plot serve as landmarks at the time of measurement. When establishing permanent sample plots, it is important to select stakes made of durable materials. For example, concrete stakes are appropriate where occasional fires occur [***Recipe-T12***].

Table 3 Information to be recorded at the establishment of plots

Information	Remarks
Location (latitude, longitude)	Information measured using GPS is recorded. Information of coordinate system used should also be recorded.
Altitude	Altitude at the location.
Inclination angle	Inclination angle along the central line.
Forest type	Classification (evergreen forest, deciduous forest, afforestation, etc.)
Azimuth	Azimuth along the central line.
Disturbance history	History of fire or selection cutting should be recorded, if any. In that case, duration of disturbance should be recorded in as much detail as possible.
Conditions of surrounding areas	Recording of land use in surrounding areas

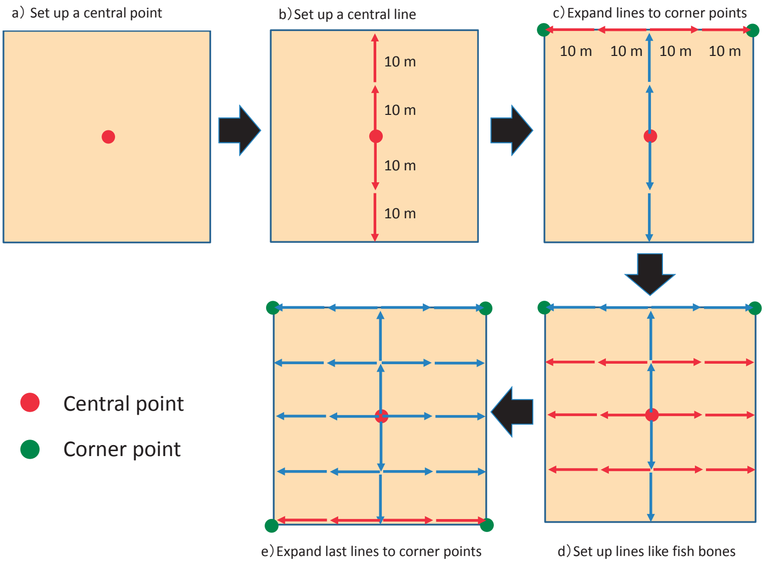


Figure 3 Procedure for establishing sample plot (a square of 40 m × 40 m)

Table 4 Stake materials used for establishing plots

Stake materials	Plot type	Characteristics
PVC pipe	Permanent/ Temporary	Available at a relatively low cost, however, vulnerable to fire and susceptible to degradation in direct sunlight.
Metal including aluminum	Permanent	High cost, but durable
Concrete	Permanent	Durable and fire resistant, but extra labor is needed when establishing.
Wood	Permanent/ Temporary	Available at a relatively low cost. Low durability depending on the type of wood.

TIPS

Easy-to-use tools for measuring horizontal distance are widely used today. In case such equipment is not available, it would be convenient to prepare a conversion table to convert slope distance to desired horizontal distance.

3 Measurement of plot

3.1 Tools required for inventory

Tools required for inventory survey for estimating forest carbon stocks are shown in Table 5. Other tools may be required depending on the target area, but these tools are enough for measuring the breast height diameter (DBH) and tree height.

Table 5 Tools required for inventory

Tool	Number	Remarks
Tape measure (about 10 m)	>1	For measuring DBH
Laser range finder	1	For measuring tree height
Label	A large number	For identifying individual tree to be measured. Material should be vinyl, plastic, aluminum, etc.
Staple gun	>1	For securing the label to the tree
Marker	>1	For recording the location of measurement and for marking to avoid double measurement.
Binoculars	>1	For identifying tree species
Pole pruner	1	For collecting samples to identify tree species
Slingshot	1	For collecting samples in places where a pole pruner does not reach.

3.2 Members of team

Two staff per team are needed for the inventory; one for measuring DBH and the other for recording data (Table 6, Photo 1). In general, the tree height is measured after measuring DBH; however, if these works are carried out simultaneously by teams, time for the inventory can be saved.

3.3 Measurement of DBH

The procedure for basic measurement is as follows:

- Record the position of a tree selected as a measurement object (if needed),
- Assign a unique identifying number to the tree and attach a tag,
- Measure the tree’s diameter at breast height,
- Mark the measurement height on the tree,
- Identify and record the species,
- Measure the tree height (when required), and
- Record other pertinent information.

Table 6 Number of staff required for inventory

Role	Desired number of staff	Remarks
Staff for entering data of tree census	1-2	Work efficiency will be improved with staff who have an overview of the entire project.
Staff for measuring DBH	1-2	With more than one staff, measurement of DBH and labeling can be done separately.
Staff for measuring tree height	1-2	Depending on the number of tools for measuring tree height.
Staff who can identify plant species	1-2	Identification of plant species and data entry may be done by the same staff.

(1) Tools

(2) Inventory carried out by a team made up of two staff

Photo 1 Inventory in the field

3.3.1 Recording a tree position selected as a measurement object

The sample plot explained in section 2.6.2 is divided into 16 square subplots (10 m × 10 m). Each sample plot uses a nested plot structure. It should be noted that DBH threshold of the trees designated as measurement objects differs depending on the subplot (see Figure 2).

In the permanent sample plot, the positions of the trees should be recorded for the second and subsequent measurements, and the route of measurement should also be determined. The positions of individual trees can be recorded easily and clearly by attaching the code number in each subplot. Moreover, if the trees are numbered in a regular pattern, for example, in a counterclockwise direction from the stake used as the starting point, it will be easy to tell if any tree has disappeared when future measurements are carried out [***Recipe-T13***]. Double measurement can be avoided by simply recording the subplot number where the individual tree designated as the measurement object is located.

All individual trees designated as measurement objects must be assigned a unique number, and then the number must be engraved on a tag, such as a commercial aluminum tag, and attached to the individual trees (Photo 2). When it is difficult to attach the tag to the tree, the number should be written directly on the stem using paint or the position should be recorded using the abovementioned subplot code system.

3.3.2 Measurement of DBH

In general, tree diameter is measured at 1.3 m above the ground. When measuring the stem using a tape measure, wrap the measuring tape firmly, not loose or sagging, around the stem. Before measuring the diameter of the individual tree, the condition at the measurement point should be checked. If there is a swelling that would distort the true diameter, then that place should be avoided. Similar, if a climbing liana is wrapped around the tree, remove it before measuring the diameter. In such a situation, field annotations such as “measured without climber” and “measuring position moved to avoid swelling” should be written down immediately before they are forgotten. In some cases, stems are thickly covered by bryophytes in the cloud forests. In that case, carefully remove the bryophytes on the position of the DBH measurement. In addition, carefully determine the measurement position if the tree has buttress roots. The measurement should always be made at the height from the point of 50 cm above the top of the buttress (Photo 3).

Photo 2 Marking of measurement position and labeling

Photo 3 Diameter measurement above the buttress

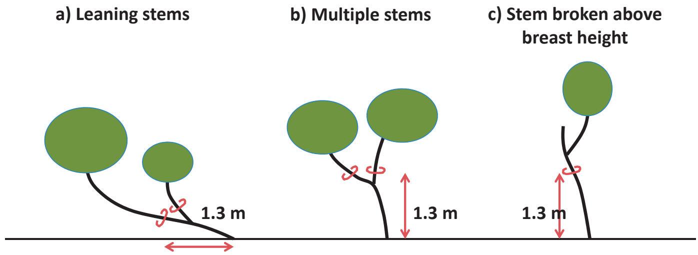


Figure 4 Example of measuring DBH for irregular stems

Individual tree stem to be measured is not necessarily straight and single. The DBH measurement of a leaning tree should be made at 1.3 m length from the base (Fig. 4a). The measurement of DBH of multiple stems should be made at 1.3 m from the base of the tree (Fig. 4b). If the main stem is withered or broken but not dead, the DBH of the tree should be measured at 1.3 m above the ground in the same manner as the regular measurement (Fig. 4c). In addition, the measurement of DBH should be made from the upper side of the slope, and it is better to mark the position of the measurement using paint for the next measurement (Photo 2).

3.3.3 Tools to be used

Carefully choose the tools when measuring DBH. For example, with calipers, the DBH is measured not once, but twice, with the second measurement being made at right angles to the first, and then the average value is used. If a tape measure is used, the DBH might become confused with the girth at breast height (GBH). It is important to be sure that the value recorded is the correct one. In addition, the same type of measurement tool should be used for all measurements of the same type. For example, some DBH measurements should not be made with an ordinary tape measure and others with slide calipers, or both a diameter tape and an ordinary tape measure should not be used.

TIPS

When the DBH measurement is carried out by two or more teams, confirm the inventory methods in advance. The discrepancy in the measurement value among the inventory teams can be reduced by checking the inventory method.

3.4 Measurement of tree height

In a tropical forest, it is often difficult to measure tree height, because it is difficult to observe the tops of the trees. If measurement objects are selected by a sampling procedure that takes the size structure into consideration, then the height of only some individual trees needs to be measured and the tree height of unmeasured trees can be determined from a DBH–tree height curve. As shown in Fig. 5, if the measurement of the tree height is carried out within the selected subplot, labor can be saved.

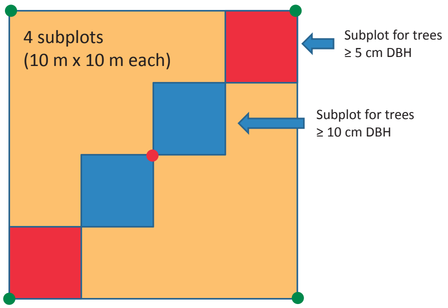


Figure 5 Example of effective measurement of tree height using subplots

In the red subplots, individual trees with DBH of 5 cm or larger are measured. In the blue subplots, DBH of 10 cm or more is measured. In other plots (yellow), tree height is not measured.

Moreover, it is important to verify the definition of the tree height used, because some engineers may use commercial tree height.

3.5 Identification of tree species

After measuring the DBH and height of trees, the tree species need to be identified, as allometiric equations for calculating carbon stocks use wood density (WD) in some cases. Identification of tree species is difficult in the tropical forest due to the presence of a large number of tree species. When identification of tree species is difficult, try to identify as much as possible, preferable to the genus level.

When unknown species are found in the field inventory, take a note of their features as much as possible such as the leaf arrangement (alternate, opposite, compound, etc.) and the color of the bark and sap. Collect as many sample leaves as possible for later identification by experts.

3.6 Measurement of leaf litter layer

The leaf litter layer is composed of fallen leaves and branches, including dead wood on the mineral soil. Dead wood greater than 10 cm in diameter is measured as explained in the following section (see 3.7).

The measurement of leaf litter layer is made by 1) creating a certain size of frame on the forest floor, 2) collecting fallen leaves and branches in the frame, and 3) measuring the total dry weight in the laboratory. In general, a square frame (50 cm × 50 cm) is enough to collect the required amount of samples (Photo 4).

Dry weight of all dead wood smaller than 10 cm in diameter collected in a slightly larger frame (e.g., a square of 2 m × 2 m) is measured in the laboratory. The dead wood collected in accordance with this procedure is too large to bring to the laboratory. Therefore, after measuring the fresh weight in the field, create a subsample for measuring dry weight.

(1) Creation of a square (50 cm × 50 cm)

(2) After collecting leaf litter in the square

Photo 4 Measurement of leaf litter layer

TIPS It is advisable to put the samples collected in the frame in a paper bag as they can be put directly into the drying oven.

3.7 Measurement of dead wood

Dead wood is defined here as all dead wood material measuring more than 10 cm in diameter. Dead wood consists of various forms such as stump, standing dead trees (snag), fallen logs, and branches. In this manual, plot-based method is applied to measure dead wood in the plot.

3.7.1 Definition of decomposition class

The first step for measuring the weight of dead wood (necromass) is to determine the wood volume in any form. Wood density is used for converting wood volume into weight, but the decomposition degree greatly varies, depending on the individual dead wood. Thus, the wood density also varies.

The decomposition classes were defined by Chao et al. (2008) as:

Class 1: Material was recently dead, with more than 75% of the wood intact and hard, and sometimes still with fine twigs attached.

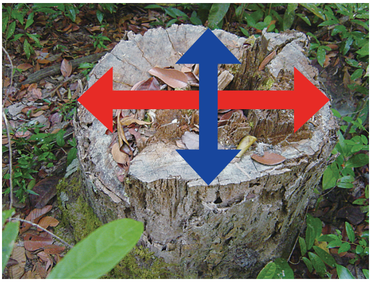
Class 2: Material was damaged, the log had experienced some decay, and was also applied to piece of wood where the bark had gone but the heartwood remained solid.

Class 3: Material was at least 75% soft and rotten, into which a machete blade could easily enter and which collapsed when stepped on.

TIPS Differences between Class 2 and Class 3 are easily identified using a nail. A nail can easily enter the wood in Class 3, but it seldom enters the wood in Class 2.

3.7.2 Stump

To know the amount of stump in the degraded forests is important, as a large number of stumps can be found in the degraded forests. First, measure the two directions perpendicular to the diameter of the stump (Photo 5). Then, measure the height from the surface of the stump to the ground. The height of the stump with irregular surface should be measured in the middle of the highest and lowest surface.



(1) Directions of measurement

(2) Measurement of stump

Photo 5 Measurement of stump diameter

3.7.3 Standing dead trees

Measure the DBH and height of standing dead trees. Measurement of the height of standing dead trees can be omitted using the DBH–tree height curve. Determining the decomposition class is also necessary. Standing dead trees still with fine twigs attached soon after withering are classified as Class 1, while standing dead trees whose small twigs have been dropped and only large branches remain on the trees are classified as Class 2. When the stem is broken, measure the height to the point where stem is broken and the diameter in the middle of the broken stem.

If the height of the broken stem is less than 4 m, measurement of the diameter can be made at the midpoint of the stem, while the measurement is difficult for the higher broken stem. In that case, DBH is used as an alternative value.

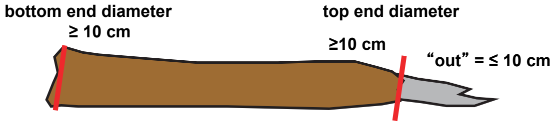


Figure 6 Measuring threshold of downed dead trees

3.7.4 Fallen trees

Typical methods for measuring the amount of fallen trees are the plot inventory method and the line transect method. In this manual, measurement using a plot inventory method is explained.

All fallen trees in the sample plot with more than 10 cm of end point diameter are measured. However, the extended part with less than 10 cm in diameter is ignored (gray part in Fig. 6). On the other hand, a part of fallen trees that extended outside the plot (red lines in Fig. 7) are not measured, while fallen trees within the plot are measured completely (blue lines in Fig. 7).

Based on these criteria, the length and diameter at both ends of fallen trees within the plot should be measured (Photo 6). In addition, the decomposition class should be recorded.

(1) Measurement of diameter

(2) Measurement of length

Photo 6 Measurement of fallen tree

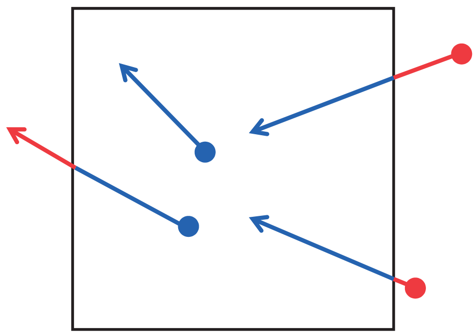


Figure 7 Measurement standard for falling dead wood in plot
Blue indicates measuring targets and red indicates beside the targets. ● are the locations of the roots.

TIPS It is advisable to use a caliper for measuring the diameter, as a part of the fallen tree is buried in the soil in some cases.

4 Data analysis for measuring carbon stock

In this chapter, methods of measuring carbon stocks using data obtained from the sample plots are explained.

4.1 Calculation of aboveground biomass

To estimate plant carbon stock in the plot, first, calculate the above-ground biomass (AGB) using allometric equation. In this manual, the following generic equation developed by Chave et al. (2014) is used:

$$AGB = 0.0673 * (\rho D^2 H)^{0.976}$$

where D (cm) is DBH, H (m) is total height, and ρ (g cm^{-3}) is wood density.

Species-specific wood density is recorded in some tree species. However, species-specific wood density is unavailable in most tree species. In that case, default values in South America (0.60 g m^{-3}) and genus average can be used to estimate AGB. For more detail about species-specific wood density data, the following database is useful (see the following database for reference):

Global Wood Density Database
(http://datadryad.org/repo/handle/10255/dryad.235)

In the absence of wood density data of tree species, try to find the mean value at the genus level and then the mean value at the family level. Still, if related data cannot be found, use the default value by continent (Table 7).

Table 7 Wood density default values in tropical regions

Region	Wood denisty (g cm^{-3})
Tropical Asia	0.57
Tropical America	0.60
Tropical Africa	0.58

Source: Reyes et al. (1992)

For a tree that has a DBH of 20.5 cm, a total height of 16.1 m, and a wood density of 0.60 g m^{-3}, the AGB is calculated as follows:

$$AGB = 0.0673 * (0.60 * (20.5)^2 * 16.1)^{0.976}$$
$$= 0.0673 * (4059.6)^{0.976} = 223.8 \text{ kg}$$

After summation of the calculated AGB using tree census data in the plot, AGB per hectare can be calculated as follows:

$$AGB_h = (Area_h \,/\, Area_{plot}) * AGB_{plot}$$

where AGB_h is the estimation of AGB per hectare, $Area_h$ (Mg ha^{-1}) is the area of one hectare, $Area_{plot}$ is the area of the sample plot, and AGB_{plot} is plot-level estimation of AGB (Mg 0.16 ha^{-1} in this manual).

If the AGB_{plot} is 25 Mg, AGB_h is 156.25 Mg ha^{-1}.

$$AGB_h = (1 \,/\, 0.16) * 25$$
$$= 6.25 * 25 = 156.25 \text{ Mg ha}^{-1}.$$

4.2 Calculation of belowground biomass

Similar to AGB, belowground biomass (BGB), consisting of coarse and fine roots, is also estimated using some equations. In this manual, the following generic equation developed by Mokany et al. (2006) is used:

$$BGB_h = 0.489 * AGB_h^{0.890}$$

where BGB_h is the estimation of BGB per hectare, and AGB_h is the estimation of AGB per hectare. After estimating AGB_h, we can simply estimate BGB_h using the abovementioned equation.

On the other hand, some allometric equations can estimate individual belowground biomass (Niiyama et al. 2010) and whole-tree biomass, including belowground parts (e.g., Sato et al. 2015). In this case, BGB per hectare can be calculated after summation of calculated BGB using tree census data in the plot.

4.3 Litter layer mass

Because a sample of the litter layer is collected in a determined plot, just determine the coefficient for converting the sampling area per hectare. Where 150 g of dry weight of litter layer is obtained in a 50 m × 50 m square, litter layer mass per hectare value (Lt_h) is calculated as follows:

$$Lt_h = Lt_s * (10000 / A_s) = 150 * (10000/0.25) = 150 * 40000 = 6{,}000{,}000 \text{ g} = 6{,}000 \text{ kg}$$

where Lt_s is litter layer mass in the plot (g), and A_s is the sampling area (m^2).

4.4 Calculation of dead wood mass

To estimate dead wood mass, we initially calculate the volume of each dead wood piece. Then, we converted the volume to dry mass using wood densities based on decomposition class (see section 3.7.1). Some literature values are useful to adopt estimation of dead wood mass. For example, wood densities in three decomposition classes are estimated in Amazonian forests, Peru (Chao et al. 2008; Table 8).

Table 8 Example of wood density in each decay class

Decomposition Class	Wood density (g cm^{-3})
1	0.55
2	0.41
3	0.23

Source: Chao et al. (2008)

4.4.1 Stump

The volume of stump can be calculated using the Huber's formula.

$$V = A * L * 100$$

where V is the volume (cm^3), A is the sectional area at the middle (cm^2), and L is the height of the stump (m). If the cutting end is shaped like an ellipse, the sectional area is calculated using the following equation:

$$A = (d_1/2) * (d_2/2) * \pi$$

where d_1 and d_2 are the two orthogonal diameters.

For example, for a stump that has 64 cm and 70 cm as the orthogonal diameters and 0.7 m height, the volume is calculated as follows:

$$V = A * L * 100 = (64/2) * (70/2) * \pi * 0.7 * 100 = 246{,}301 \text{ cm}^3$$

If the stump has "class 2" of decomposition class, the mass is calculated as follows:

Mass = V * $WD_{\text{decomposition class}}$ = 246,301 * 0.41 = 100,983 g = 100.98 kg

4.4.2 Standing dead trees

The volume of standing dead trees can also be calculated using the Huber's formula.

$V = A * L * 100$

The area of breast height of standing dead trees is a substitute for the sectional area of middle (A) in some cases. For example, for a dead tree that has a DBH of 25.6 cm and a height of 6.5 m, the volume is calculated as follows:

$V = A * L * 100 = (25.6/2)^2 * \pi * 6.5 * 100 = 334{,}567 \text{ cm}^3$

If the dead tree has "class 2" of decomposition class, the mass is calculated as follows:

Mass = V * $WD_{\text{decomposition class}}$ = 334,567 * 0.41 = 137,172 g = 137.17 kg

4.4.3 Fallen trees

The volume of fallen trees, V (cm^3), can be calculated using Smalian's formula as follows:

$$V = L\left[\frac{\pi\left(\frac{D_1}{2}\right)^2 + \pi\left(\frac{D_2}{2}\right)^2}{2}\right]$$

where L (m) is the length of the piece of fallen tree, and D is the diameter (cm) at either end.

For example, for a fallen log that has 20 cm and 10 cm at either end and a length of 1.8 m, the volume is calculated as follows:

$V = 100 * 1.8 ((\pi (20/2)^2 + \pi (10/2)^2) /2) = 180 * (314.2 + 78.5) / 2 = 35{,}343 \text{ cm}^3$

If the fallen log has "class 2" of decomposition class, the mass is calculated as follows:

Mass = V * $WD_{\text{decomposition class}}$ = 35,343 * 0.41 = 14,491 g = 14.49 kg

Here is another example. For a fallen log that has rectangular cross-sections with 20 cm and 10 cm on sides at both ends and 1.8 m in length (like a square pole), its volume and mass (with “class 2” of decomposition class) are simply calculated as:

$$V = 100 * 1.8 * 20 * 10 = 36{,}000\ \text{cm}^3$$

$$\text{Mass} = V * \text{WD}_{\text{decomposition class}} = 36{,}000 * 0.41 = 14{,}760\ \text{g} = 14.76\ \text{kg}$$

4.4.3 Calculation of dead wood mass

Similar to AGB, dead wood mass also needs to be reported as per hectare estimate. If total the amount of dead wood is 800 kg in a 0.16 ha plot, the per hectare estimate of dead wood mass is calculated as follows:

$$\text{Dead Wood Mass} = 800 * (1/0.16) = 5{,}000\ \text{kg} = 5.00\ \text{Mg ha}^{-1}$$

4.5 Conversion from biomass to carbon stock

We should also estimate forest carbon stock per area (i.e., Mg C ha^{-1}) as well as plant biomass. To estimate carbon stock of biomass and dead wood mass, “carbon fraction of dry matter (CF)” defined by IPCC 2006 GPG will be used.

If AGB_h is 125 Mg ha^{-1} in a sample plot, carbon stock ($AGB_{h\text{-}c}$) can be calculated as follows:

$$AGB_{h-c} = AGB_h * CF$$

$$= 125 * 0.47 = 58.75\ \text{Mg C ha}^{-1}$$

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