Forest Carbon Stock Measurement

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Asia Network for Sustainable Agriculture and Bioresources (ANSAB)

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Forest Carbon Stock Measurement: Guidelines for measuring carbon stocks in community-managed forests

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About 500 billion tons of carbon are stored in vegetation worldwide. Deforestation and forest degradation alone accounts for 17.4% of the world's greenhouse gas emissions. The problem is especially acute in tropical and subtropical forests where carbon stocks are decreasing at an alarming rate of 1-2 billion tons a year. Initiatives in forest conservation and enhancement which take into account the livelihood concerns of poor and socially marginalized people dependent on the forests can help to address this dire situation.

In this context, 'Reducing Emissions from Deforestation and Forest Degradation (REDD)' has recently received special attention in the climate-change debate. When properly designed, REDD schemes can provide a sound bridging mechanism in the transition towards a low-carbon economy. They can contribute to improving rural livelihoods, promoting good forest governance, delivering biodiversity objectives, and increasing resilience and adaptive capacities to climate change.

Carbon accounting in a forest is one of the most crucial steps for successful implementation of REDD projects. The process needs to meet international standards and, at the same time, be manageable in a cost-effective manner within the local context. This is why the development of these Nepal-specific guidelines was undertaken. They detail the entire process of forest carbon measurement using simple language and illustrations, from the initial delineation of a project area to leakage monitoring once REDD activities have been implemented. We hope that they will be helpful for technicians, researchers, students, communities, and other interest groups who will be involved in REDD projects in the country.

Financial support for the preparation of these guidelines came from the Norwegian Agency for Development Cooperation (NORAD) through the project entitled 'Design and setting up of a governance and payment system for Nepal's Community Forest Management under REDD' which is currently being implemented by the Asia Network for Sustainable Agriculture and Bioresources (ANSAB), the International Centre for Integrated Mountain Development (ICIMOD), and the Federation of Community Forest Users Nepal (FECOFUN). Our very special gratitude goes to the department team of the NORAD Civil Society for their support.

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Finally, I am grateful to all the staff of ANSAB, to the experts who participated in the various workshops on the Forest Carbon Stock Measurement Guidelines and to the many other individuals who provided their time, documents, or ideas to the project.

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List of Acronyms

AGB	above-ground biomass
ANSAB	Asia Network for Sustainable Agriculture and Bioresources
BGB	below-ground biomass
CF	community forest
CaF	carbon fraction
CFM	community forest management
CFUG	Community Forest User Groups
cm	centimeter
DBH	diameter at breast height
dm	dry matter
DFRS	Department of Forest Research and Survey
FECOFUN	Federation of Community Forest Users, Nepal
FMG	Field Measurement Guidelines
G	grams
GIS	geographic information systems
GPS	global positioning system
ha	hectare
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
LRPs	local resource persons
Mg	mega gram (1000 kg, or one metric ton)
mm	millimeter
NORAD	Norwegian Agency for Development Cooperation
NTFPs	non-timber forest products
QA	quality assurance
QC	quality control
RC	resource consumption
RE	resource extraction
REDD	Reducing Emissions from Deforestation and Forest Degradation
SOC	soil organic carbon
SOP	standard operating procedure
T	ton (mega gram, 1000 kg, or metric ton)
TISC	Department of Forest, Tree Improvement and Silviculture Component
UNFCCC	United Nations Framework Convention on Climate Change
VCS	Voluntary Carbon Standard
VDC	Village Development Committee
WWF	World Wildlife Fund

Chapter one: Introduction to and use of the guidelines

Reducing emissions from deforestation and forest degradation (REDD) has gained major attention in international climate negotiations. Evolving discussions on REDD have brought forests to the forefront of both climate-change mitigation and adaptation. Among others, successful REDD programs require reliable, accurate, and cost-effective methods for measurement and monitoring of forest carbon storage. Despite the involvement of several academic research and development organizations in Nepal, common, reliable, and user-friendly forest carbon measurement methodologies are still lacking.

'Forest Carbon stock Measurement: Guidelines for measuring carbon stocks in community-managed forests' was prepared by the technical team of Asia Network for Sustainable Agriculture and Bioresources (ANSAB) in consultation with the Project Management Unit-ICIMOD; international and national experts; and key stakeholders. It is a product of the REDD pilot project 'Design and setting up of a governance and payment system for Nepal's Community Forest Management under Reducing Emissions from Deforestation and Forest Degradation', an initiative implemented by the Asia Network for Sustainable Agriculture and Bioresources (ANSAB), International Centre for Integrated Mountain Development (ICIMOD), and Federation of Community Forest Users, Nepal (FECOFUN) with financial support from the Norwegian Agency for Development Cooperation (NORAD).

The guidelines describe methods, procedures, and steps for measuring organic carbon stored by forest land-use systems. They introduce globally accepted equipment, instruments, methodologies, procedures, and standards for forest carbon measurement and offer a detailed recipe for using them more efficiently and effectively. In other words, blended methods and procedures are presented coherently to make them applicable to a wide range of eco-regions and management regimes. The guidelines offer guidance on defining participatory boundaries with the help of remote-sensing maps and tools, as well as a complete set of procedures on application of remote sensing, GIS, and ground inventory. They provide, in short, precise, accurate, reliable, and user-friendly methodologies for forest carbon measurement which are adapted to Nepal's specificities.

1.1 Objectives of the guidelines

The guidelines are broadly intended to be a reference for measuring and monitoring forest carbon stocks. Also, they aim to provide a set of carbon measurement procedures applicable to the forestry and agroforestry land-use systems of Nepal. The guidelines are expected to meet international standards as defined by the Intergovernmental Panel on Climate Change (IPCC) and Voluntary Carbon Standards (VCS). They seek to offer a range of flexible methodologies for measuring, monitoring, and estimating forest carbon with several options applicable to forests from different ecological and management regimes. In addition, they are intended to serve as user-friendly training material for forest users.

1.2 Organization of the guidelines

The methodology and procedures to be used to estimate carbon stocks and their changes over time in forests are simple step-by-step procedures using standard carbon inventory principles and techniques.

The procedures used emphasize the training of forest technicians and local resource persons (LRPs). Procedures are based on data collection and analysis of carbon accumulating in the above-ground biomass; below-ground biomass, litter, and soil carbon of forests using verifiable state-of-the-art methods (see Figure 1).

1. Delineation of project boundaries
2. Stratification and boundary mapping of stratum
3. Pilot inventory for variance estimation
4. Capacity building and orientation of the locals
5. Field measurements in the permanent plots (AGB, BGB, soil, dead wood, herbs & litter)
6. Data analysis (calculation of carbon stock density)
7. Leakage analysis belt and monitoring
8. Report preparation

Figure 1: Forest carbon measurement process

Chapter one of the guidelines introduces this book and project, lists the objectives of the guidelines, gives the brief organization of this book, and discusses the preparation process for the guidelines. **Chapter two** of the guidelines describes processes of delineation, stratification, and boundary mapping of the project area; explains a pilot inventory for variance calculation; and a method for calculation of optimal sample plots. **Chapter three** describes the layout, the size, and the shapes of the permanent sample plots used during the collection of data on forest carbon measurement. It also details the various carbon pools measured in the forest. **Chapter four** is mainly concerned with the planning and management of field measurement activities. This chapter provides a list of equipment required to measure carbon in the field. Similarly, it gives a clear idea about managing the team so that work is carried out smoothly in the field. **Chapter five** is about permanent plot navigation and forest carbon stock measurement. Further measurements of leaves, herbs and grass, soil organic carbon, and saplings and trees are discussed in detail under sub headings. **Chapter six** describes the analysis of various carbon pools measured in the forests. Analysis of above-ground tree biomass, below-ground biomass, leaf litter, herbs, and soil organic carbon is explained in detail. **Chapter seven** attempts to clarify the concept of leakage in the REDD projects. It provides an idea of identifying leakage belts and methods of leakage monitoring and lists the ways of reducing leakage. **Chapter eight** is focused on quality assurance (QA) and quality control (QC). It discusses the QA and QC to be maintained during measurement, laboratory analysis of samples, data entry, and analysis.

1.3 Preparation process

The process for preparing the guidelines involved various methods such as discussions, interactions, and consultations with experts, practitioners, and users. A logical succession of steps was followed throughout the preparation.

a. Overview of desk appraisal

The process began with an in-depth review of the relevant literature which included the following.

- A Guide to Monitoring Carbon Storage in Forestry and Agro-forestry Projects (MacDicken1997)
- Complementary methodologies developed by international organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the Voluntary Carbon Standard (VCS) (Eggleston et al. 2006; VCS 2007)
- Nepal-specific community-forest management best practices (Dahal et al. 2004; Banskota et al., 2007; Karky and Banskota 2007)
- Measurement methodologies applied in the country by the WWF/Winrock International (Gurung 2008)
- Guidelines for Inventory of Community Forests, Nepal, by Department of Forests (CPFD 2008).

After careful comparison of the different international standards to be followed for forest carbon estimation, the carbon fraction (CF) 0.47 default value (IPCC 2006) described in Table 1 is proposed to convert the biomass value of standing trees into carbon stock.

Table 1 : Comparison of summary processes for forest carbon estimation

Methods	IPCC (2006)	Pearson et al (2007)	MacDicken (1997)	VCS (2007) and CCB (2008)
Criteria for stratification	Climate zone, ecotype, soil type, management regime within land- use types	Vegetation, soil, topography	Land-use, vegetation, slope, drainage, elevation, proximity to settlement	According to the guidance provided by IPCC
Carbon pools to measure	Above-ground biomass, below- ground biomass, dead wood, litter, and soil organic matter), as well as emissions of non-CO_2 gases	Above-ground biomass, below-ground biomass, dead wood, litter, soil organic carbon, and wood products	Above-ground biomass/necromass, below-ground biomass (tree roots), soil carbon and standing litter crop	Consider the same pools covered under the IPCC guidelines
Methods / values for estimation	Allometric equations for trees Ratio of BGB to AGB for tropical dry forest 0.56 for < 20 tons AGB/ ha 0.28 for > 20 tons AGB/ ha Carbon fraction (CF): 0.47 (default value for all parts)	Allometric equations for trees, destructive harvesting for shrubs, herbs and litter Root : Shoot ratio BGB = exp (-1.0587 + 0.8836 x in AGB) Carbon content = 0.5 (50% of total biomass)	Equation for moist climate, annual rainfall (1,500 – 4,000 mm) $y = 38.4908 – 11.7883 D + 1.1926 D^2$ Root : Shoot ratio = 0.10 or 0.15 Carbon content = 0.5 (50% of total biomass)	According to the guidance provided by IPCC

Source: Gurung (2008)

b. Individual expert consultations

The draft guidelines were reviewed by three individual experts; namely, Professor S.P. Singh, Former Vice Chancellor, Garhwal University – Ecologist India; Dr. Steven De Greze, Terra Global Capital, USA; and Dr. Meine van Noordwijk, World Agroforestry Center (ICRAF).

c. Organizational expert consultations

In order to ensure that the guidelines would be acknowledged and deemed to be legitimate by the government, they were also submitted for review to the Department of Forest Research and Survey (DFRS) and the REDD - Forestry and Climate Change Cell - of the Ministry of Forest and Soil Conservation. Their inputs and comments have been incorporated into this book.

d. Input collection and interaction with stakeholders

As part of the preparation process, inputs, comments, feedback, and suggestions were collected through organizing a stakeholder consultation workshop. A total of 27 experts from the government, I/NGOs, academic institutions, and civil society organizations took part in the workshop. Experts from the DFRS and REDD Cell presented their findings from reviewing the guidelines. Comments and input from the workshop were incorporated into the guidelines and given back to the experts for final review.

Chapter two: Boundary mapping and pilot inventory

The first step in forest carbon measurement is delineation of the project boundaries which is then followed by making a pilot inventory. Each activity is discussed in detail in subsequent paragraphs.

2.1 Delineation of project boundaries

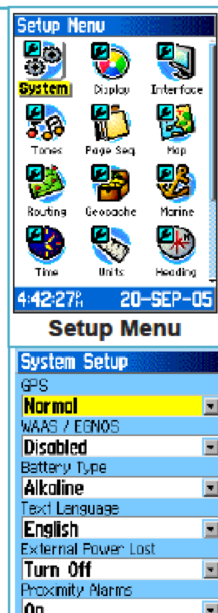
Spatial boundaries of the particular area need to be clearly defined to facilitate accurate measuring, monitoring, accounting, and verification. A watershed might be a natural entity of a spatial project area. Spatial boundaries can take the form of permanent boundary markers, e.g., rivers and /or creeks, mountain ridges; spatially explicit boundaries (identified with global positioning system [GPS] apparatus); and/or other methods. Many tools are available for identifying and delineating project area boundaries; and these include remote sensing, e.g., satellite images from optical or radar sensor systems; aerial photos; GPS; topographic maps; and land records. Larger areas across the landscape can be defined by specific boundary descriptions using GPS-based coordinates on topographic maps or by using satellite images.

Software such as geographical information systems (GIS), ARC hydro extension of ARC GIS (ESRI software) or the BASINS extension tool for ARC view software are used to delineate watershed areas of spatial project boundaries. Contour lines and data on drainage networks are commonly available to define watershed boundaries of specific project areas. For this purpose, high resolution satellite images (e.g., Geo eye 0.5 m resolution) are extremely useful if they can be obtained. GPS points are used for geo-referencing as required for increased accuracy and precision on satellite images and GIS data: available satellite images and global positioning systems (GPS Map 60CSx, Garmin) are used for verification.

Box 1: Procedure for handling a GPS receiver

How to set up GPS (GPS Map 60CSx, Garmin)

- Go to the Main Menu page by pressing the **Page Key** (There are six pages: Satellite page, Trip composer, Map page, Compass, Altimeter and Main Menu).
- Highlight **Setup Menu** and press **Enter Key**. When the set up page is displayed, highlight the **System** icon and press Enter again.
- Set the following system set up using the **Roger Key:**
  GPS –Normal
  WAAS/EGNOS – Disabled
  Battery Type – Alkaline
  Text Language – English
  External Power Lost – Turn Off
  Proximity Alarms – On
- Quit this page using the **Quit Key.**



Box 2: Procedure for setting up the unit

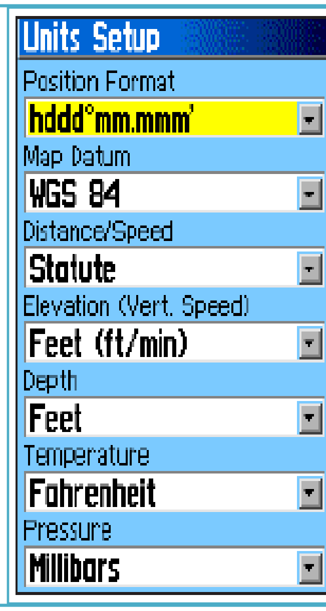
Unit set up (GPS Map 60CSx, Garmin)

Setting up the unit is an important step and can be done as per the following instructions.

In the **Set-up Menu** page**,** highlight the **Units** icon, and press **Enter.**

Set the following Units Set up using the **Roger Key.**

- **Position Format – Users UPS** (choose a coordinate system according to your working area)
- **Map Datum – WGS 84** (It is a description of the geographic location for surveying, mapping, and navigation.)
- **Distance/Speed – Matrices**
- **Elevation (vert. Speed) – Meter**
- **Depth – Meter**
- **Temperature – Celsius/Fahrenheit**
- **Pressure - Millibars**



2.2 Forest boundary delineation

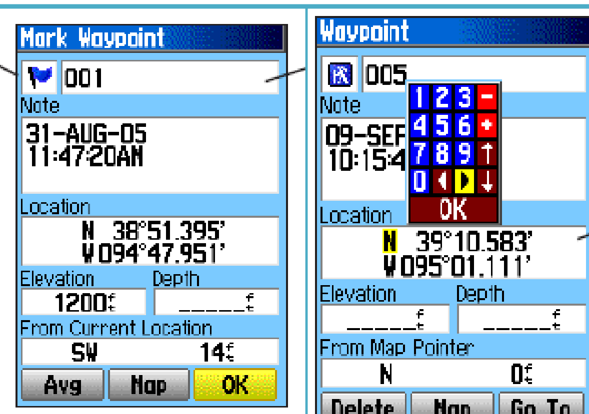
Individual forest blocks within the project area are mapped jointly by GIS experts, forest technicians, and members of community forest user groups (CFUGs) in a participatory way. High-resolution satellite images printed on a large scale are used to find the different land-cover and natural boundaries and to trace individual forest blocks easily. GPS (GPS Map 60CSx, Garmin) tracking is carried out to delineate different management methods for forests in confusing areas, i.e., where the natural boundary cannot be clearly observed.

If high-resolution satellite images are unavailable, GPS tracking is the most accurate and efficient alternative method for boundary delineation, even if the process is time consuming. The procedures for marking current location and delineating the forest boundary using GPS are described in Box 3 and Box 4 respectively. Each forest block should be traced on to base maps first and then digitized on Arc View or ARC GIS software for data input. The data tracking from the GPS receiver is downloaded as a shape file, e.g., DNR Garmin software can be used. The areas of individual forest blocks are estimated after digitizing and editing the data downloaded.

Box 3: Process for marking the current location

Marking the current location (GPS Map 60CSx, Garmin)

- To quickly capture your current location, press and hold the **Mark Key** until the **Mark Waypoint** page appears.
- At the top of the screen, a 3 digit Waypoint name appears as a default: highlight it and press the **Enter** key.
- Use the Rocker to enter the name of the captured Waypoint and press **OK** on the keyboard (You can also edit the Waypoint and manually load new Waypoints using this page). Press **OK** at the bottom right of the **Mark Waypoint** page and then press quit to exit.
- To find the Waypoint press **Find Key** to open the **Find Menu.**
- Highlight the **Waypoints'** icon and press Enter.
- Highlight any Waypoint and press Enter, information on the Waypoint selected is displayed.



Mark Waypoint Page

Box 4: Process for marking the current location and delineating the forest boundary using GPS

Delineating the forest boundary using GPS (GPS Map 60CSx, Garmin)

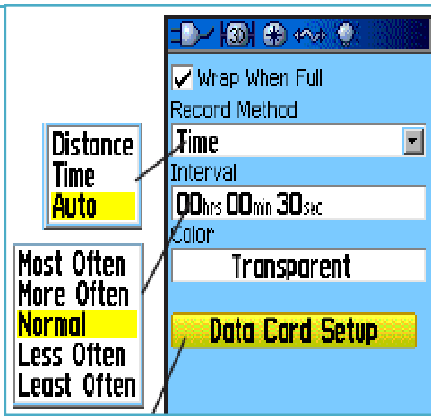
Tracks are used to depict line and polygon features.

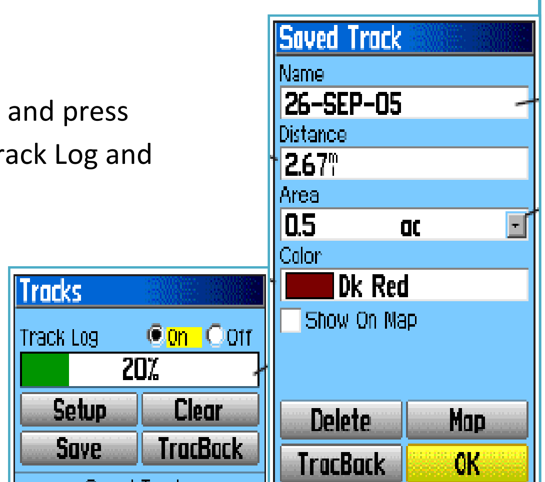
- **To set up a** track log press twice on the **Menu key** to open the **Main Menu** page.
- Select the **Tracks'** icon and **press Enter** to **open the Track** page.
- Highlight the **Set up** button, and Press **Enter** to open the **Track Log Set up** page and set up the following.

  Record Method – Distance

  Interval – 5m

  Color - Transparent
- To survey CFUG boundaries select **On** in the Track Log and press **Enter** once: similarly, after tracking select **Off** in the Track Log and press **Enter** once.
- To save the entire Track Log, open the **Track page** and activate the **Save Button**. A message asks if you want to save the entire track. Select **Yes** and press **Enter** to save the track.
- Tip: You can rename the track in the same way used for saving Waypoints.
- Press **OK** and exit from this page.





Saved Track Page

Photo 1: Participatory delineation of the community forest boundary using high-resolution satellite images

Photo 2: Tracking the forest boundary using GPS

2.3 Stratification of the project area

Once the project area has been delineated, it is essential to collect basic information on features such as land use and land cover as well as data on the vegetation and topography. Data for the project area (e.g., watershed area) can be geo-referenced and traced on to a base map. A base map specifies the details of the project area by indicating the different land-use categories (forest, water bodies, open land, agricultural land, and so forth) and is developed with high-resolution satellite images preferably. Strata are areas distinctly different from each other in forest types, density, and species; and as such they will have different amounts of carbon stored.

To make strata as homogeneous as possible, a forest within the project area is divided into different layers or blocks. Remote-sensing software (ERDAS Imagine, Definiens Developer or ILWIS) is used for land-cover classification and forest stratification.

A preliminary field visit is organized within the entire study area to improve the accuracy and precision of the representation. Strata and sub-strata are identified using the expert knowledge of local foresters. The entire project area can be stratified into approximately homogeneous units on the basis of the following parameters.

- **Forest types -** Tropical sal (*Shorea robusta*) forest, tropical evergreen forest, subtropical deciduous hill forest, and temperate forest are regarded as forest types.
- **Dominant tree species -** Sites containing a dominant tree species are regarded as one-stratum types.
- **Stocking density of trees -** Within a dominant type, sites are separated further if they differ substantially in stocking density. Remote-sensing analysis is used to identify forest

areas which differ in tree density. 'Sparse' and 'dense' can, for example, be major types of forests.

- **Age of trees -** Sites with distinct age classes are stratified further, as carbon sequestration differs markedly with the age of the stand.
- **Aspect and position of hill slopes -** Within a dominant forest type, sites differing in aspect and position on a hill slope are also stratified further because the rate of carbon sequestration varies in relation to these factors. For example, a stand on the south aspect would have far greater productivity than one on the north aspect.
- **Altitude -** Forest blocks are selected within altitudinal ranges above mean sea level as vegetation types differ according to altitudinal variation. It is sensible to design elevation strata that represent forests within a 300-500m range in altitude.
- **Physical boundary -** The boundary of the forest block is determined on the basis of easily visualized boundaries (i.e., rivers, roads, ridges, and so on)**.**
- **Site quality -** Site quality tells us how much timber a forest can potentially produce. The productivity of forest land is defined in terms of the maximum amount of volume that the land can produce over a given amount of time. Site quality is measured as an index related to this timber productivity.

2.4 Pilot inventory for variance estimation

A preliminary inventory then needs to be completed to estimate the variance of the carbon stock in each forest stratum and to provide a basis for calculating the number of permanent plots required for the inventory. It is carried out by laying 10 to 15 circular plots randomly in each forest block and/or stratum within the project boundary. Random selection is important in order to cover the natural variability present within the different forest blocks and /or stratum. The plot size is dependent on tree density (MacDicken 1997). Possible plot sizes are presented in Table 2. The default plot dimension is 250 m^2 with 8.92 m radius as this surface is suitable for moderate to dense vegetation (MacDicken 1997).

A carbon inventory is more complex to carry out than a traditional forest survey because a different variance may be associated with each carbon pool (MacDicken 1997). Therefore, all trees above and equal to 5 cm in diameter at breast height (DBH) within sample plots have to be measured and recorded on the data sheet (Karky and Banskota 2007; Karky 2008). A sample datasheet for a pilot inventory is given in Annex 1.

Table 2: Plot radius for carbon inventory plots

Plot size [m^2]	Plot radius [m]	Typical area per tree [m^2]	Tree density
100	5.64	0 to 15	Very dense vegetation, stands with large numbers of stems small in diameter, uniform distribution of larger stems
250	8.92	15 to 40	Moderately dense woody vegetation
500	12.62	40 to 70	Moderately sparse woody vegetation
666.7	14.56	70 to 100	Sparse woody vegetation
1000	17.84	More than 100	Very sparse vegetation

Source: MacDicken (1997)

2.5 Calculation of optimal sampling intensity and number of permanent sample plots

It is impossible to measure every tree within a forest. Statistical sampling theory explains how measuring only a fraction of the trees provides a measure of the biomass that is good enough to be used in carbon accounting. To quantify what ’good enough’ means, it is important to distinguish between two concepts: accuracy and precision.

Accuracy refers to how close a measured quantity is to its actual value, whereas precision expresses how reproducible a measurement is. Ideally, measuring biomass is both accurate and precise. One can imagine, however, a measurement technique that yields very different values every time a measurement is taken, but which provides accurate measurements when large numbers of individual measurements are averaged. Such a technique would be accurate but not precise. In contrast, a technique that continuously reproduces values within a narrow range but which are far from the actual values will be precise but not accurate. The measured values will be characterized by a systematic bias.

In classic sampling theory, the accuracy of a measurement system is established by setting a (often arbitrary) reference standard and repeatedly measuring this reference standard and calculating how far the measurements are to the set reference. The precision is usually quantified practically, using the width of the confidence interval around the mean, while the accuracy is quantified by the difference between the measured mean and the reference level. For forest inventories, the reference measurement could be carried out by a team of truly experienced foresters, and the precision of a field crew can be tested by comparing the biomass values from the experienced foresters with that of the field crew. The precision of a forest inventory can be tested by performing multiple forest biomass inventories within the same forest stratum.

In other words, measurements that are ’good enough’ are both accurate – meaning that measurements should be identical to measurements carried out by a team of truly experienced foresters – and precise – meaning that the width of the confidence interval around the mean should be sufficiently small. As a rule of thumb, one half of the width of the 95% confidence interval around the mean divided by the mean should be less than 10% within a stratum. If it is greater than that, more samples should be taken within that stratum, or the stratum should be split into two more homogeneous strata. The problem with this approach is that one needs to know the standard deviation of the measurements to know how many samples one needs, and, to know the standard deviation, one has to have carried out the measurements. In practice, it is best to adapt the sampling design and number of samples iteratively (see procedure below).

In these guidelines, sample plots are established on a permanent basis to estimate changes in the forest carbon stock, as using permanent plots is more accurate statistically for recording tree growth than resampling the forest blocks or strata every time. Permanent plots that are known to local managers, however, have the potential to be managed differently and may end up with more carbon stock than their surroundings. The existence of this possible bias can be checked by conducting comparative measurements in the surrounding area in subsequent evaluation. Permanent plots are also labeled inconspicuously to minimize the risk.

It is important to note that, by dividing the project area into relatively homogeneous strata, one can increase the accuracy and precision of measuring and estimating carbon. A stratified sampling design decreases the costs of monitoring because it diminishes the number of sampling plots required to acquire a set precision compared to a non-stratified sampling design. A stratified sampling design will allocate a greater number of plots in strata that have greater variability and, therefore, focus the sampling efforts in areas in which more accuracy is needed. Please note that a sampling design in which a single-stratum approach is used for every stratum will yield a greater number of plots than the multiple-strata sampling design described below. This is because a single-stratum sampling design for every stratum will result in the required precision on every stratum. On the other hand, the multiple stratum approach will result in the required precision only in the full area, which is a less stringent requirement.

The following procedure is carried out to calculate the sampling intensity (number of permanent sample plots) required for an above-ground forest biomass inventory.

Step 1. Identify the required precision level. A required precision with a value of 10% of the mean, calculated as the half-width of the 95% confidence interval, is frequently used.

Step 2. Select the location of the 10-15 preliminary sampling plots per forest stratum – the selection can be either completely random, or can be a random selection from a pre-set rectangular grid of sampling plots. Plots can be laid out or distributed randomly within each stratum using a standard sampling method or software like Hawths' tool of ARC GIS (for more details please visit www.spatialecology.com).

Step 3. Estimate carbon stock per tree, per plot, per ha, and mean carbon stock per ha for each of the preliminary sampling plots.

Step 4. Calculate the standard deviation of carbon [Mg C ha^{-1}] for all the plots.

Step 5. Calculate the number of plots required using the following statistical eq. (i) for multiple strata:

$$N = \frac{A}{AP}\,;\, N_i = \frac{A_i}{AP} \quad \text{……………………………… eq. (i)}$$

where,

N	=	maximum possible number of sample plots in the project area [dimensionless];
A	=	total size of all strata, e.g. the total project area [ha];
AP	=	sample plot size (constant for all strata) [ha];
N_i	=	maximum possible number of sample plots in stratum i [dimensionless];
i	=	index for stratum [dimensionless]; and
A_i	=	the size of each stratum i [ha].

With the above information, the total sample size (minimal number of sample plots to be established and measured) in all the strata can be estimated as eq. (ii):

$$n = \frac{\left(\sum_{i=1}^{L} N_i \cdot s_i\right)^2}{\frac{N^2 \cdot E^2}{t^2} + \left(\sum_{i=1}^{L} N_i \cdot s_i^2\right)} \quad \text{……………………………… eq. (ii)}$$

where,

n	=	total number of sample plots (total number of sample plots required) in the project area [dimensionless];
i	=	project strata number from 1 until L [dimensionless];
L	=	total number of strata [dimensionless];
N_i	=	maximum possible number of sample plots in stratum i [dimensionless];
s_i	=	standard deviation for each stratum i [dimensionless];
N	=	maximum possible number of sample plots in the project area [dimensionless];
E	=	desired level of precision;
t	=	sample statistic from the t-distribution for the 95% confidence level: t is usually set at 2 since sample size is unknown [dimensionless]; and
s	=	standard deviation for each stratum i [dimensionless].

The following eq. (iii) can be used to distribute the total number of sample plots over the different strata:

$$n_i = n \cdot \frac{N_i \cdot s_i}{\left(\sum_{i=1}^{L} N_i \cdot s_i\right)^2} \quad \text{.. eq. (iii)}$$

where,

n_i	=	number of sample plots for stratum i [dimensionless];
i	=	project strata number from 1 until L [dimensionless];
n	=	total number of sample plots (total number of sample plots required) in the project area [dimensionless];
N_i	=	maximum possible number of sample plots in stratum i [dimensionless];
s_i	=	standard deviation for each stratum i [dimensionless]; and
L	=	the total number of strata [dimensionless].

Step 6. Visit the field to measure the biomass on the number of sample plots derived in step 5.

Step 7. Calculate the true relative half-width of the confidence interval around the mean for each stratum and compare these to the required values of 10%. If the required precision of 10% is not attained, either split or merge the strata or update the number of samples required to get the required precision based on the standard deviation from all the sampling plots.

Repeat steps 5-7 until the required precision is attained or by following the adaptive sampling design as described in Section 2.6. UNFCCC (2009) provides an alternative method for calculating the number of sample plots for carbon measurement activities.

2.6 Adaptive sampling design

Adaptive sampling is a strategy for maximizing the value of biomass inventory samples by continuously adapting the number of samples taken in each forest stratum. Adaptive sampling design works well when sampling individuals are spatially clustered, elusive, or hard to detect. Additionally, adaptive sampling is robust in situations where variability is difficult to estimate before sampling, and it is, therefore, an ideal sampling strategy for forest biomass inventories. Adaptive sampling contrasts with conventional sampling techniques, such as stratified random sampling, in which all of the sample units are selected prior to the actual inventory. In adaptive sampling, an initial set of sampling units (plots) is selected, either randomly or through a systematic approach, but plot distribution over individual strata is continuously optimized. Plots are added repeatedly until the desired precision is attained. The basic steps for an adaptive sampling strategy are as follows.

1. Stratify the forest based on elevation classes, forest types, visible stocking (i.e., trees per ha), and aspect. Select 3 to 5 forest strata.
2. Obtain information on variability. When no previous data from biomass inventories are available, the variability of the biomass stock density must be obtained from the literature or from a preliminary survey. When part of the inventory has been carried out already, however, all plots sampled in previous iterations should be used for calculating the number of sample plots required.
3. Use the procedure mentioned in these guidelines to obtain the number of plots required per stratum.
4. In one iteration step, measure about 25% of the total plots required by the sampling design, evenly distributed over each stratum.
5. Estimate biomass stock, variability, and precision for the entire forest and for each individual stratum. Sampling precision can be obtained using the following formula:

$$Precision\ level = \frac{SE_{ST}\ t_{0.05,n-1}}{X_{ST}}\ \% \qquad \text{eq. (iv)}$$

   where, SE_{ST} is the standard error of the stratified mean, X_{ST} is the stratified mean, and n is the number of sample plots.
6. If the desired precision is met, sampling can be finalized.
7. If the precision is relatively large in at least one stratum (e.g., precisions greater than 30%), revision of the stratification by splitting forest strata into more homogeneous sub-strata, or merging smaller strata to attain more samples within a stratum should be considered. Re-calculate the biomass stock, variability, and precision for the new strata as explained in step 4.
8. Re-calculate the plots required based on the empirically measured precision levels and the newest stratification following the procedures mentioned in these guidelines. Repeat steps 2 through 6 until the desired precision over every stratum is attained.

It is possible that steps 7 and 8 may result in either more, less, or the same number of plots allocated for one or more strata.

Figure 2 summarizes the adaptive sampling design concept. In addition, Table 3 contains an example of a 4-iteration sampling design. Assume a forest with 2 strata and for which variability data were obtained from the literature. The required number of sample plots based on the literature data is 32 and 64 for each of the two strata. After sampling 25% of the required samples in the first iteration of the sampling, the variability was re-calculated, and the sampling design re-evaluated. The precision of the dense stratum was fairly large (55%)

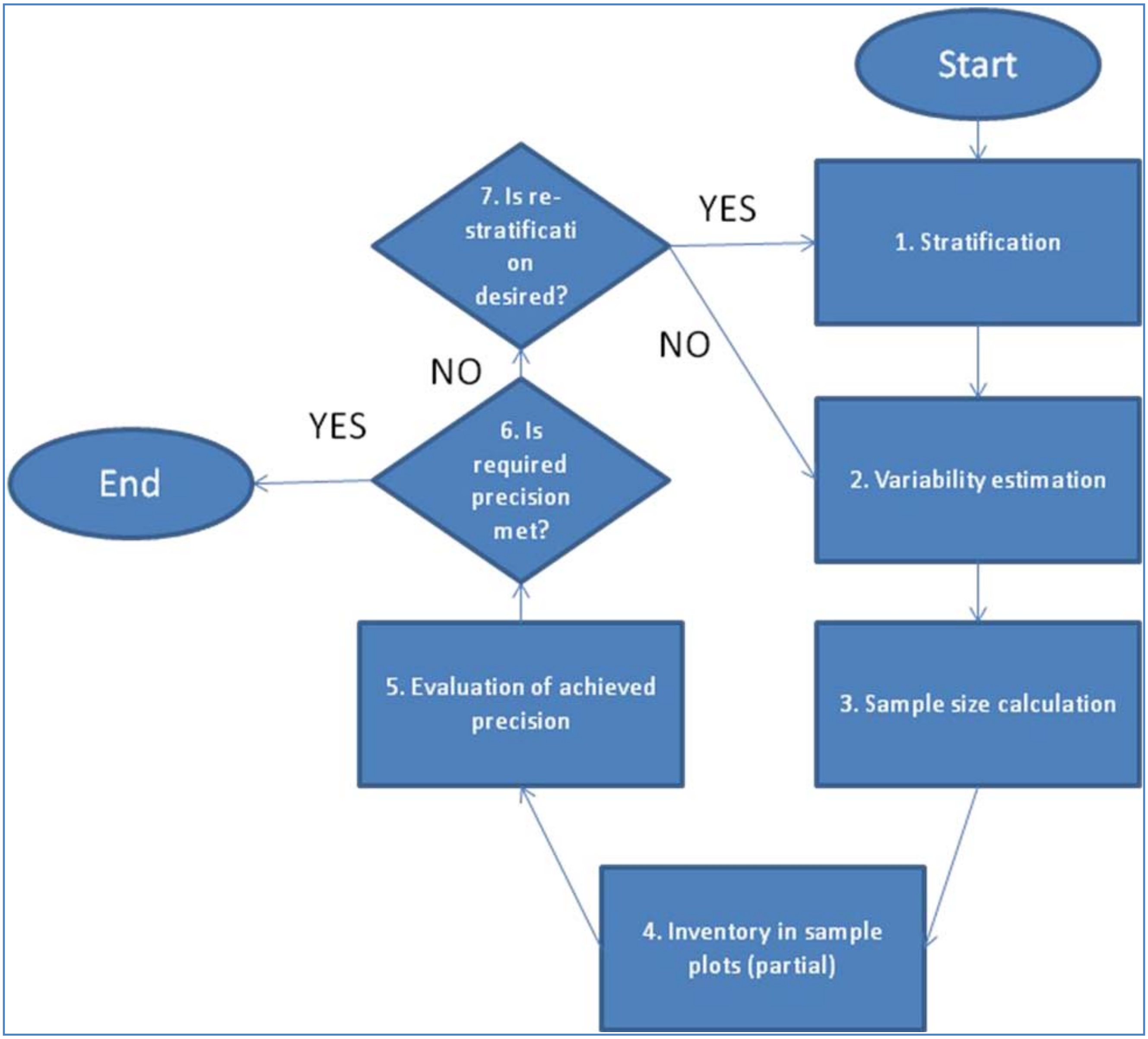
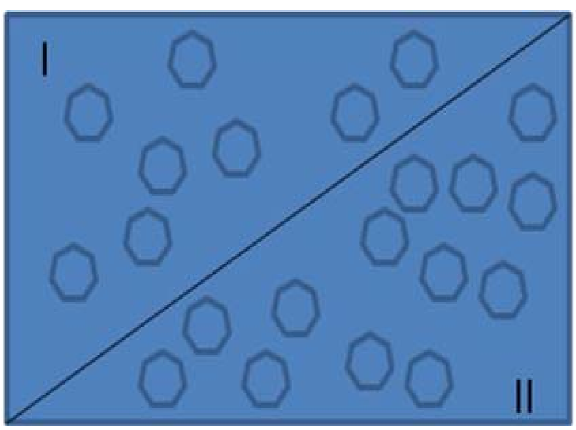


Figure 2: Adaptive sampling procedure

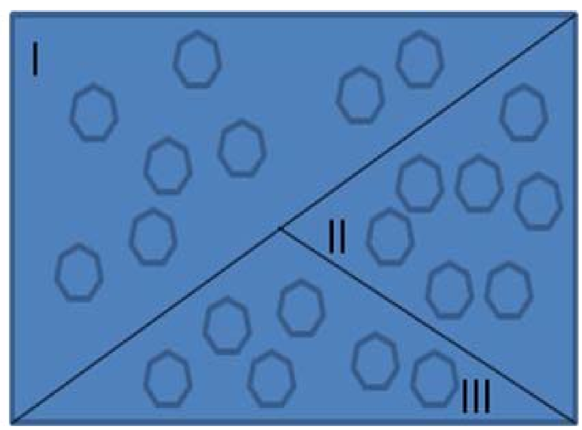
and, therefore, this stratum was divided into a 'dense coniferous' and a 'dense deciduous' stratum (Figure 3). After a second field campaign, the precision was re-calculated based on all 49 available samples. The sampling design was re-evaluated again, and the next set of sampling locations was set. At the end of the last iteration the total precision attained was 10% and sampling ended.

Table 3: Description of an adaptive sample design at various iterations

Iteration	Stratum	Total number of sample plots required	Sample plots measured during iteration	Total sample plots already measured at the end of iteration	Precision attained at the end of iteration
1	Sparse	32	8	8	25%
	Dense	64	16	16	55%
	Total	**86**	**24**	**24**	**35%**
2	Sparse	20	5	13	15%
	Dense - coniferous	46	12	20	35%
	Dense - deciduous	30	8	16	35%
	Total	**96**	**25**	**49**	**25%**
3	Sparse	21	5	18	11%
	Dense - coniferous	32	8	28	17%
	Dense - deciduous	26	9	25	17%
	Total	**79**	**22**	**71**	**15%**
4	Sparse	21	3	21	11%
	Dense - coniferous	32	4	32	12%
	Dense - deciduous	26	1	26	12%
	Total	**79**	**8**	**79**	**10%**



(a)



(b)

Figure 3: Illustration of stratification during the adaptive sampling process

Note that sample biomass inventory plots from previous sampling locations should always be retained when calculating variability: if new strata are added, however, the strata of the existing sample biomass inventory plots must be re-evaluated.

Chapter three: Permanent plot distribution and layout

Establishing permanent plots with appropriate sizes and shapes is another task to be completed for forest carbon measurement.

3.1 Permanent plots

The number of permanent sample plots is dependent on the size and types of forest stratum. Plots used must be of the same size as those used in the pilot survey. A base map is used to produce locations of random sample plots. Plots are laid out or distributed randomly within each stratum using standard sampling methods or software (e.g., Hawths' tool of Arc GIS) as shown in Figure 4 (details on Hawths' tool can be obtained from www.spatialecology.com). Coordinates of each plot are also generated. The plots' coordinates are then loaded into the GPS; e.g., using DNR Garmin software. Cemented or wooden pillars marked with permanent paint are used to fix the center of each plot permanently. The marking in the center of the plots has proved to be very valuable in annual monitoring as GPS alone could give a few meters of difference in locating the center of the permanent plot for subsequent measurements.

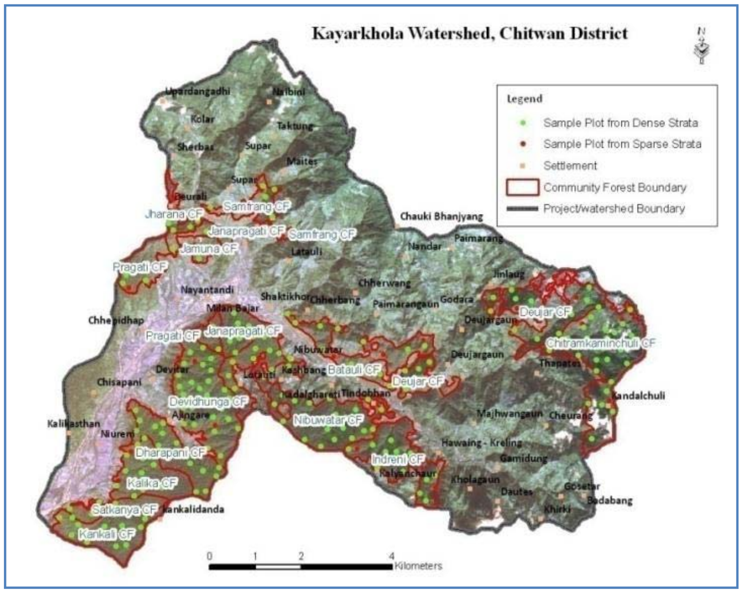


Figure 4: Map showing the distribution of permanent plots

3.2 Size and shape of sample plots

Forest carbon measurement can be carried out in both rectangular and circular plots. Nevertheless, circular samples are recommended for the study because they are relatively easy to establish. As discussed previously, the radius of each plot is dependent on the density of the forest, the default being an 8.92 m radius for moderately dense vegetation. As illustrated in Figure 5, several sub plots are established within each plot for specific purposes: inside of the 8.92 m radius plot, a sub plot with a 5.64 m radius is


Photo 3: Laying out a 0.56 m plot

established for saplings; a sub-plot with a 1 m radius is established for counting regeneration; and a sub plot with a 0.56 m radius is established for sampling leaf litter, herbs, grass, and soil.

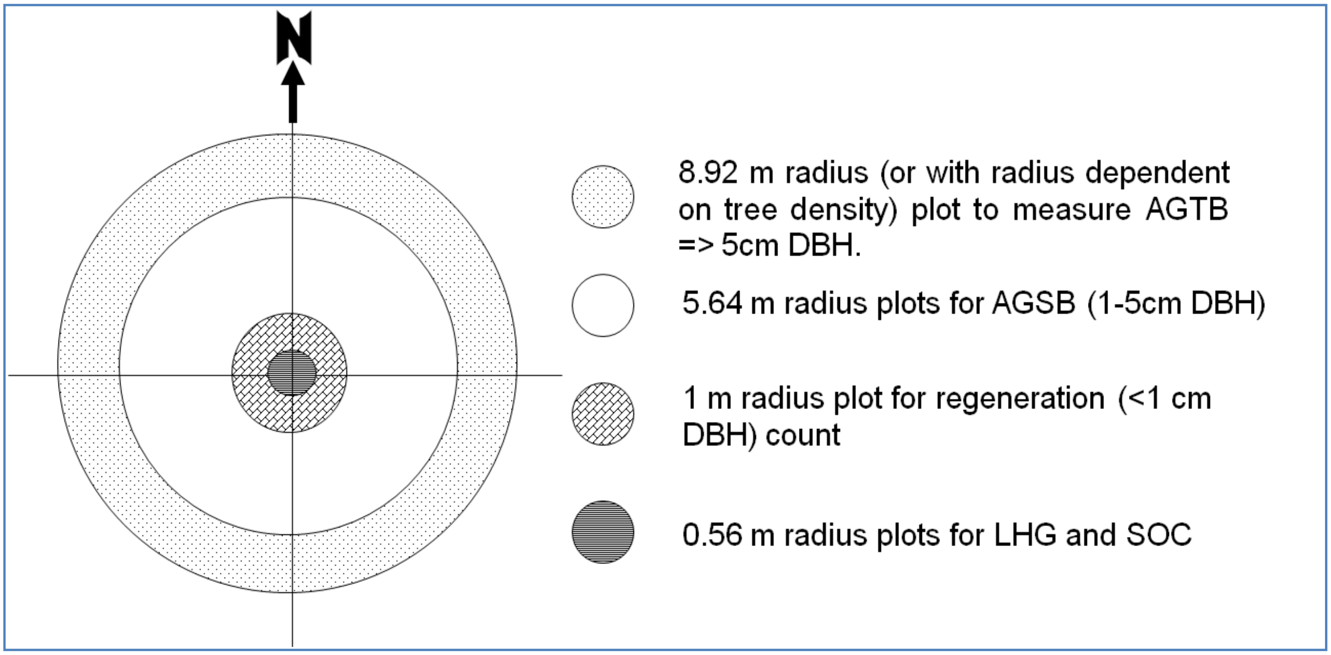


Figure 5: Sampling design of circular plot (default size)

3.3 Carbon pools to measure

The following carbons pools (also see Figure 6) will be measured in forest carbon estimation.

a) Above-ground tree biomass (AGTB)

b) Above-ground sapling biomass (AGSB)

c) Below-ground biomass (BB)

d) Soil organic carbon (SOC)

e) Leaf litter, herbs, and grass (LHG)

f) Dead wood and fallen stumps (DW)

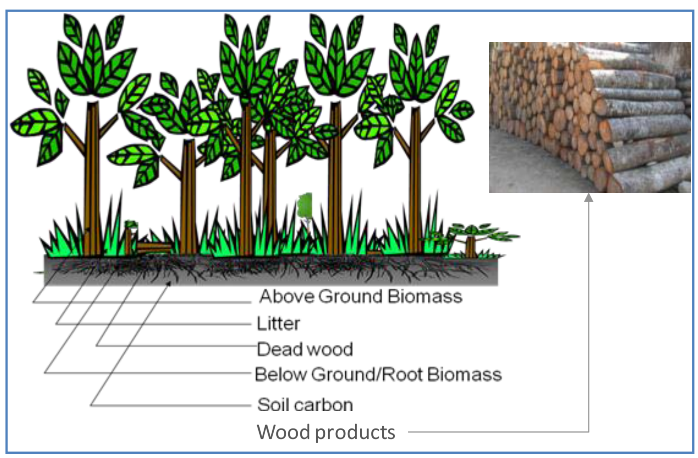


Figure 6: Various forest carbon pools

If the necromass portion of the carbon pool is not significant in the area due to frequent removal of dead wood for use as fuel by local communities, this pool should not be measured.

Chapter four: Planning and preparation of field measurement

Thorough planning is imperative for efficient fieldwork: it helps to avoid mistakes, to recognize hidden opportunities, and, more generally, to ensure that operations run as smoothly as possible. A good planning process also enables the working group to understand more clearly what they have to accomplish and when they are expected to accomplish it.

Before going to the field to establish plots on a new site, a sufficient number of field teams should be formed (middle level forest technicians, local resource persons, and community forest users' group [CFUG] members), instruments and materials should be procured, responsibilities should be delegated, field work should be scheduled, appointments should be made with the user group, forms for recording field data should be photocopied, and maps should be printed. These activities are explained in detail in the paragraphs below.

4.1 Gathering and organization of equipment

Gathering the materials required before moving to the field is crucial. All instruments and pieces of equipment should be collected early enough so that they can be prepared, checked, and calibrated in advance. The operational team has to ensure that every instrument is functioning, so that field work can take place without any disturbance. A complete checklist should be prepared so that no materials are left behind: this checklist will also be useful during field work as the team moves from one location to the other.

Photo 4: Equipment used during forest carbon measurement

A sample check list is given in Photo 4 and Table 4. The principal features of and methodology for using advanced equipment is given in Annex 2.

Table 4: List of instruments and materials required to carry out forest carbon measurement

S.N.	Items	Purpose
1.	GPS	Boundary survey, stratification, and locating plots
2.	Base map	Plot navigation
Permanent plot establishment		
3.	Rope	For plot boundary delineation
4.	Linear tape	For locating plot boundary and for distance measurement
5.	Chalk	For marking the trees within the boundaries temporarily before permanent tagging and for ensuring they are measured.
6.	Metal tags for tree	For permanent marking of trees
7.	Metal tag for plot	For showing the direction to the permanent plot from different vantage points
8.	Enamel	For numbering metal tags
9.	Brush	For numbering metal tags
10.	Hammer	For fixing metal tags on tree
11.	Cemented pillar	For setting up the plot center
12.	Khanti (spade)	For digging soil
13.	Nails	For placing the tags
Leaf litter and herb/grass collection		
14.	Plastic bags	White plastic bags to collect samples and big plastic bags to collect and weigh herbs, grass, and leaf litter
15.	Cloth bags for leaflets and twigs	Herbs, grass, and leaf litter should be collected in cloth bags since plastic bags may get torn.
16.	Knife or sickle	For cutting herbs and grass
17.	Weighing machine	For weighing herbs, grass, and leaf litter
18.	Scissors	For cutting herbs and grass
Soil sample collection		
19.	Metal scale	For measuring soil depth
20.	Soil sample core	For collecting soil samples from various depths
21.	White cloth or masking tape	For tightening the soil core so that no soil comes out
22.	Soil sample hammer	For bearing down on the soil core while collecting sample
23.	Weighing machine	For weighing samples
24.	Kuto (trowel)	For taking out soil core from the soil depth
Height and diameter measurement		
25.	Linear tape	For measuring the distance between the tree and the measurer; and to establish the plots
26.	Diameter tape	For measuring the diameter of the tree at breast height
27.	Clinometer	For measuring the ground slope, top, and bottom angle to the tree
28.	Vertex IV and transponder	For measuring tree height and establishing circular plots without the use of tapes and clinometers.
29.	Callipers	Can be used instead of a diameter tape to measure the diameter of trees.

4.2 Human resource management

After gathering all the equipment and materials required for forest carbon measurement, another important element is team formation and training-cum-orientation. Forest carbon measurement should be carried out with care to ensure the collection of complete data. Once the data collecting team leaves one location, it is not practical to revisit the area at a later date to collect missing data. Hence, a well-trained and well-managed team is needed.

The participation of local persons is also a must since building the capacity of and transferring knowledge to local and indigenous communities are an intrinsic part of REDD in order to make it efficient and effective. The following paragraphs describe how to form and train a good data-collection team.

4.2.1 Team formation

A good team should be formed and trained well in advance of their first field operation to ensure a satisfactory standard for data collection. Generally, each field team should have 3-5 members for the pilot inventory (data collection sheet for the pilot inventory is given in Annex 1) and 6-8 members for the detailed inventory (data collection sheet for the detailed inventory is available in Annex 3); and one of them must be a person who knows the details of the methodology; has read these guidelines thoroughly; is able to operate all the equipment properly; takes a copy of the guidelines along to the site; and comprehends the importance of even the tiniest detail of the work described here. Teams should include at least one forest technician who has a thorough knowledge of carbon measurement; and two is the ideal because a second forest technician in the team helps to speed up operations. The remaining crew members should be local resource persons. The local resource persons taking part in forest carbon measurement should have primary-level education at least; more educated team members would further ease the measurement process. Table 5 describes the details of the work to be carried out by various crew members.

Table 5: Responsibilities of team members for forest carbon measurement

Team member	Title	Responsibilities	Equipment/ materials to be used
1	Team leader	Navigation to the plot center	GPS or compass and tape
		Determine the plot edge and trees within the plots	Vertex IV or linear tape or measuring rope
		Measurement of tree height	Vertex IV o clinometer and linear tape
		Supervision of the team and assurance of the quality of work	
		Inventory, quality assurance and calibration of equipment before going to the field and after laying out each plot	Checklist of equipment and materials

Team member	Title	Responsibilities	Equipment/ materials to be used
2 & 3	Samplers	Collection, measurement, sample preparation for herbs, grass, litter, and soil	Polybags, cloth bags, knife or sickle, weighing machine, metal scale, soil sampling core, soil sampling hammer, 'kuto'(trowel) and marking/price tags
		Mark plot center with permanent marker	'Khanti'(shovel) and plot center marker (e.g., RCC pillar, PVC pipe)
4	Plot layer	Temporarily marking trees	Chalk
		Laying out inner/core plots for sapling and seedling records	Rope, linear tape
		Counting seedlings in the innermost sub-plot	
5	Tree marker	Numbering trees with permanent marker or numbering metal stamps.	Metal tags for trees, metal tags for plots, enamel, brush, hammer, nails
6	Diameter measurer	Diameter measurement	DBH tape
		Assist team leader in determining the edge of the plot	Vertex IV, tape, clinometer, slope correction table
7	Record keeper	Record keeping of all the measurements carried out within the plot	Forms, pen, pencil

Key: RCC=reinforced concrete cement; PVC= polyvinyl chloride

4.2.2 Orientation program

Data collection has to be good enough and no compromises can be made. For that all the crew members taking part in forest carbon measurement should understand the basic ideas behind forest carbon measurement and how to use all the materials and equipment. To train the team properly, a one-day orientation program should be organized. Orientation should be carried out in two sessions, a theoretical one and a practical one in the field. Major activities to be carried out during the orientation program in general are listed in Table 6 and described subsequently.

Table 6: Major activities during the orientation program

S.N.	Activities	Time allocation
1.	Introduction to forest carbon measurement	15 minutes
2.	Importance of forest carbon measurement	15 minutes
3.	Forest carbon measurement procedures	30 minutes
4.	Demonstration and use of equipment and materials	30 minutes
5.	Field demonstration	2 hrs

Photo 5: Orientation for local resource persons

Photo 6: Field demonstration

In the first session all participants should be given classroom orientation on the importance of carrying out forest carbon measurement, the principles of forest carbon measurement, and standards of forest measurement. Every activity to be performed in the field should also be explained sequentially and in a very clear manner. In the classroom all the materials and equipment used during forest measurement should be demonstrated. Participants will get a clearer idea of use of materials and equipment once everything is demonstrated in the field.

Once classroom orientation is over, the whole crew should move to the field. Then all the activities explained in the classroom should be demonstrated. Care should be taken that all participants are actively taking part in the field demonstration. It is important to execute all the activities in sequence, i.e., plot navigation, plot establishment, herb and/or grass collection, leaf litter collection, soil sample collection, plot center marking, tree marking, diameter measurement, and measurement of tree height.

4.2.3 Detailed field measurement planning

After all the equipment and materials have been gathered and the team given orientation on field measurement, the next key step is preparing a detailed action plan for field measurement activities depending upon the funds and human resources available. Planning should be carried out in a participatory manner. Date, meeting points, contact person, and target CFUGs are agreed during the planning. A sample table (Table 7) can be helpful in the planning.

Table 7: Sample table for planning purposes

Date	Name of CFUG	Meeting point	Key contact person
25th August, 2010	Birenchowk	Birenchowk Bazar	Rana B.K. (9849XXXXXX)

Chapter five: Permanent plot navigation and field measurement

After the team is properly oriented and ready to carry out measurement activities, it has to navigate to the place where the permanent plot has been established. As soon as the team reaches the plot, it needs to collect data about the different carbon pools. Examples of datasheets for recording measurements are provided in Annex 3.

5.1 Permanent plot navigation

After loading sample plot locations on to the GPS receiver (as described in Section 3.1), sample plots are navigated to in the field by using a GPS receiver. To navigate to sample plots the **Go To** function is used. Proximity should be set up so that the center point of the sample plot for every waypoint can be approached. A base map would be helpful for field placement of plot locations on a map or image. Details of navigation to permanent plots are given in Box 5. If the location of the permanent sample plot lies on inaccessible and impractical terrain such as cliffs, roads, rivers, or cultivated land, the position of the plot center will be relocated according to the compass bearing as referenced in Annex 4.

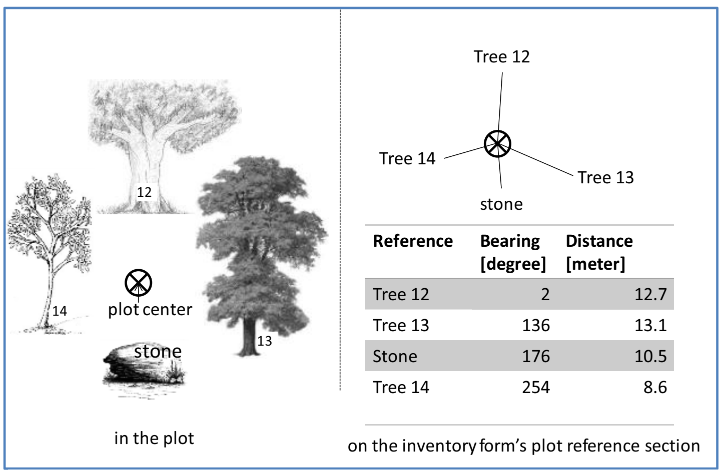
Box 5: Details for navigating to permanent plots

Navigating to permanent sample plots in the field using GPS (GPS Map 60CSx, Garmin)

- Press the **Find key**, highlight **Waypoints** and press **Enter.**
- When the **waypoints' list** appears, highlight the Waypoint involved and press **Enter.**
- When the **waypoint page** is displayed, highlight **GO TO** and press **Enter.** On the **map page** you can see the direction and distance between you and the waypoint. You can approach the point on the ground following these instructions.
- When you arrive near the radius of the point sought the GPS gives you the information by beeping until you reach the exact center of the plot.

5.2 Center point marking and referencing

Center points of all plots must be marked permanently in the field using marks such as concrete pillars, metal rods, pipes, or stone poles. No matter what object is used for marking the center, there is always a risk that it will be moved or removed. Therefore, the distances and bearing between the center and at least 3-4 permanent



Reference	Bearing [degree]	Distance [meter]
Tree 12	2	12.7
Tree 13	136	13.1
Stone	176	10.5
Tree 14	254	8.6

Figure 7: Referencing the center of the plot on the datasheet

reference points (stones or trees) should be recorded. The references should be distributed around the center.

The sketch of the plot center references, their distances, and bearings to the center must be recorded and shown on the inventory form. Besides showing the location of such references, the plot layout sketch must also indicate the geographical orientation of the plot. In addition, easily recognizable landmarks should be marked on a sketch of the plot layout (Figure 7).

5.3 Slope correction

The next step after determining the center of a plot is to delineate its boundary as prescribed in section 3.2. While placing a permanent sample plot, care must be taken to do a correction for any slopes in the area. A Clinometer can be used to measure slope angles. Most standard forestry compasses also contain a slope measure (Sylva compasses). A calculator can be used in the field to make the simple trigonometric calculation (distance on the sloping ground is equal to the cosine of the angle of the slope divided by the desired radius) necessary to determine the slope. Alternatively, a chart (attached in Annex 5) with horizontal distances calculated according to the slope angle could be taken to the field.

Photo 7: Measuring slope

5.4 Forest carbon stock measurement

After slope correction, the major work of carbon measurement starts. Here, leaf litter, herbs, and grass; above-ground sapling biomass, and regeneration; dead wood and stumps; soil organic carbon; and above-ground tree biomass are measured. Detailed methods are explained under the following sub-headings.

Photo 8: Collecting leaf litter

5.4.1 Leaf litter, herbs, and grass (LHG)

One circular sub plot of 1 square meter (0.56 m radius) in size is established at the center of each nested plot. All the litter (dead leaves, twigs, and so forth) within the 1 m^2 sub plots are collected and weighed. Approximately 100 g of evenly mixed sub-samples are brought to the laboratory to determine moisture content, from which total dry mass can then be calculated. Likewise, herbs and grass (all non woody plants) within the plots are collected by clipping all the vegetation down to ground level, weighing it (please see Box 6 to ensure correct weight measurement), placing in a sample weighing bag and bringing it to the laboratory to determine the oven dry weight of the biomass.

5.4.2 Above-ground sapling biomass, and regeneration (AGSB)

The goal of quantifying regeneration data is to analyze the regeneration status of the project area. This helps to plan processes for further forest enhancement and sustainable management practices.

Nested sub plots having a 5.64 m radius inside larger plots are established for sapling measurement. Smaller nested sub plots having a 1 m radius inside the larger nested plots are established for assessing regeneration. Saplings with diameters of > 1 cm to < 5 cm are measured at 1.3 m above ground level, while saplings smaller than 1 cm in diameter at 1.3 m above ground level are counted as regeneration.

Box 6: Things to be considered while using a weighing machine

> **Calibration weight for the scale:** Calibration of the weighing machine ensures error free weight measurement of samples. A weight of known mass can be carried into the inventory site and its mass should be checked on the scale each time the electric machine is switched on. If the weight of known mass is accurately measured by the scale the sample weighing process should be continued. Otherwise, the machine should be re-set and the scale recalibrated.

5.4.3 Dead wood and stumps (DWS)

In most cases dead wood is less abundant than live trees. Standing dead trees, fallen stems, and fallen branches with a diameter at breast height (DBH) and/or diameter ≥ 5 cm should be measured within the whole 250 m^2 plot, branches with diameters of 2-4 cm should be measured within the 100 m^2 plot, and thinner branches should only be measured within the 1 m^2 plot. A common datasheet for dead wood measurement is presented in Annex 3, Section 7.

5.4.3.1 Logged trees

Stumps may be dead or alive. If a stump is taller than 1.3 m, it should be measured in the same way as standing dead trees. If it is less than 1.3 m tall, the diameter should be measured as close as possible to the top. In addition, the height of the stump and the state of the dead wood should be recorded.

1. Note down the height and the circumference of a logged tree stump on the dead-wood measurement form.
2. Assign and note down the decay class of the tree. Use a machete to determine the decomposition class, using the following guidelines.

   CLASS 1 Sound wood: a machete/knife/khukuri cannot sink into the wood in a single strike

   CLASS 2 Intermediate wood: a machete/knife/khukuri sinks partly into the piece in a single strike

   CLASS 3 Rotten/crumbly wood: a machete/knife/khukuri cuts through the piece in a single strike

5.4.3.2 Standing dead tree

Standing dead trees are important carbon sinks and also carbon sources which need to be accounted for. The inventory process should also include this component using the data sheet given in Annex 3, Section 7.

CLASS 1 Tree with branches and twigs but without leaves
CLASS 2 Tree with no twigs, but with small and large branches
CLASS 3 Tree with large branches only
CLASS 4 Bole (trunk) only, no branches

5.4.3.3 Downed and dead wood

Fallen branches and stems should be divided into sections of roughly one meter and the exact length and diameter at the middle of each section should be recorded. For stems and / or branch fragments that are less than 1 metre long, the length and diameter at the middle should be measured. Standards to be used while measuring standing and fallen dead wood and stumps are summarized in Figure 8.

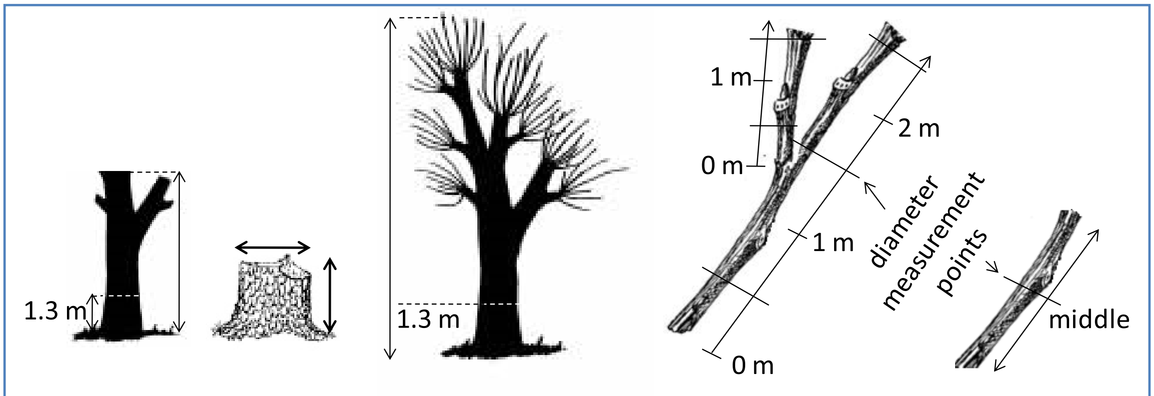


Figure 8: Measurement of standing and fallen dead wood and stumps

5.4.4 Soil organic carbon (SOC)

Soil organic carbon will be determined through samples collected from the default depth prescribed by the IPCC (2006). Near the center of all plots and/or sub-plots a single pit of up to 30 cm in depth is dug to best represent forest types in terms of slope, aspect, vegetation, density, and cover. The location of the hole is decided based on foresters' knowledge of the area. For the

Photo 9: Collection of a soil sample

purpose of estimating bulk density, three individual soil samples of approximately 100 or 300 cm^3, one each from three depths (0-10 cm, 10-20 cm, and 20-30 cm) are collected with the help of a standardized 100 or 300 cm^3 metal soil sampling corer. Similarly, one composite sample is collected mixing soils from all the three layers in order to determine concentrations of organic carbon and then weighed at a precision of 0.1 g. Around 100 g of composite sample are collected from one plot.

It is important not to modify the soil bulk density in any way during sampling. For this, a trench can be dug with a spade and a sample collected sideways. The following steps can serve as a guide for collecting soil samples.

- Dig a trench with a spade or other similar equipment.
- Orient yourself to the surface dug.
- Wood or plastic planks can be used to smoothen the exposed surface.
- Use a fine brush to remove any material from the exposed soil surface.
- Insert a core at three subsequent depths.
- Once the soil corer has been inserted into the soil to the desired depth, it is removed from the ground by pulling it outwards.
- The top and bottom (or bottom only depending on the coring tool used) of the core should be trimmed to be even with the rims. When taking cores for measurements of bulk density, care should be taken to avoid any loss of soil from the cores; if any material is lost, resampling will be needed.

All material collected in the corers and composite soil samples should be placed into sample bags which are labelled appropriately. All samples should be then transported to the laboratory for further analysis.

In addition, it is highly recommended to use a soil standard to quantify the analytical errors made by the soil laboratory. This 'standard soil' should be considered as a reference when multiple labs, technicians, and time periods are involved in soil carbon analysis. A large volume of 'standard soil' sample must be collected from random forest soil. The volume of soil collected must be sufficient so that small 'check samples' can be included every time soil samples are sent to the lab for the whole duration of the project. As a rule of thumb, one 'check sample' should be included for every 10 true samples. For example, if 300 plots are measured every year of a 50-year project, and one soil sample of 100 g is send to the lab for every plot, in total 0.10 x 300 x 50 x 100 = 150 kg of 'standard soil' is necessary. Including losses through handling, about 300 kg of standard soil must be collected.

After collection of the 300 kg of standard soil, the standard soil should be well mixed, possibly by using a mechanical mixer such as a cement mixer. If a mixer is not available or cannot be rented, manual mixing can be done, but it should be done very thoroughly and in small batches that are constantly mixed together and split again. To check the homogeneity of mixing, 10-20 samples of the standard soil should be sent to the laboratory in one batch.

5.4.5 Above-ground tree biomass (AGTB)

The DBH (at 1.3m) and height of individual trees greater than or equal to 5cm DBH are measured in each permanent circular 250 m^2 plot that is 8.92 m in radius using diameter tape, clinometers and linear tape, starting from the edge and working inwards, and marking each tree to prevent accidentally counting it twice. Highly sensitive equipment such as Vertex IV and Transponder can also be used to measure tree height directly. The application procedure is presented in Annex 2. Each tree is recorded individually, together with its species' name if identification is possible. Trees on the border must be included if > 50% of their basal area falls within the plot and excluded if < 50% of their basal area falls outside the plot. Trees overhanging into the plot are excluded, but trees with their trunks inside the sampling plot and branches outside are included. For trees of an unusual shape, a standard forestry practice should be adopted (Karky and Banskota 2007; MacDicken 1997) before all sampling operations and applied to all plots.

Photo 11: Measuring top angle of tree

Photo 10: Measuring tree diameter at breast height

Diameter at breast height (DBH) is the basic measurement standard for trees. This measurement is recorded for all trees. (Note that, for stems with irregularities, measurement is carried out according to the principles illustrated in Figure 9.) For stems that fork from the ground, each individual stem is measured separately: to indicate that they are part of the same tree, however, they are numbered by adding a letter suffix. For example, stems 12a and 12b would both be part of tree number 12. Care should be taken to ensure that the diameter tape is put around the stem exactly at the indicated point of measurement.

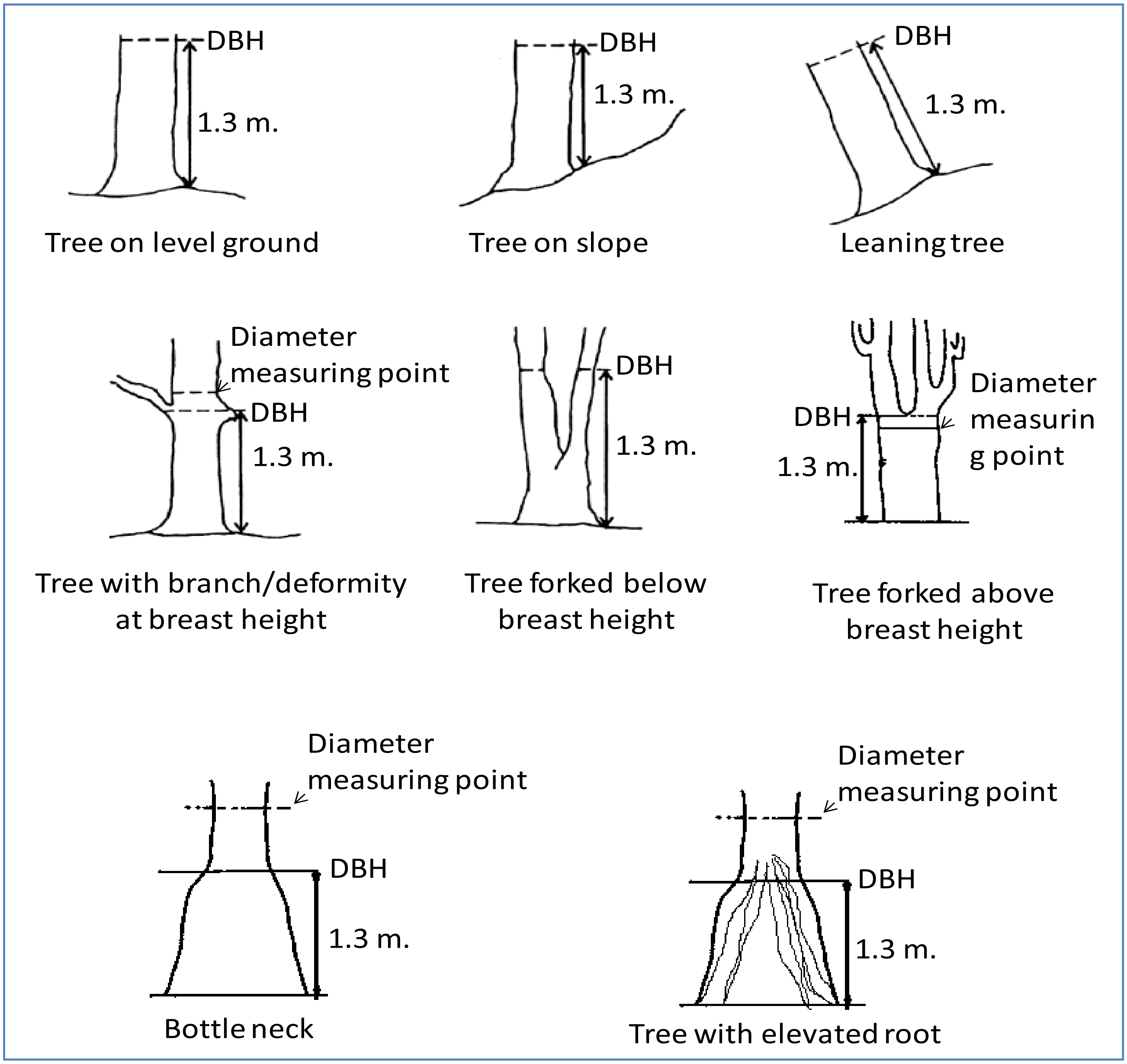


Figure 9: Standard forestry practices while measuring tree diameter at breast height

Chapter six: Data analysis

Soon after the data collection is completed, data analysis of various carbon pools measured in the forests is yet another major task to be accomplished. Analysis of all the carbon pools is explained in this section.

6.1 Above-ground tree biomass (AGTB)

An allometric equation is a statistical relationship between key characteristic dimension(s) of trees that are fairly easy to measure, such as DBH or height, and other properties that are more difficult to assess, such as above-ground biomass. Allometric equations are established in a purely empirical way on the basis of exact measurements from a relatively large sample of typical trees. They permit an estimate of quantities that are difficult or costly to measure on the basis of a single (or at most a few) measurement.

The selection of the appropriate allometric equation is a crucial step in estimating above-ground tree biomass (AGTB). Allometric equations for biomass usually include information on trunk diameter at breast height *DBH* (in cm), total tree height *H* (in m), and wood-specific gravity ρ (in g/cm^3). Baker et al. (2004) have shown that ignoring variations in wood density results in poor overall prediction of the stand (AGB). Therefore, wood-specific gravity is an important predictive variable in the regression model.

Direct wood density measurements are seldom available for trees in permanent forest stands. As a consequence, either a specific-level average (Brown et al. 1989; Nelson et al. 1999; Chave et al. 2005), or, if detailed floristic information is unavailable, a stand-level average (Baker et al. 2004) is recommended. The use of tree height as a predictive variable also improves the quality of the allometric equation. Hence, the allometric equation enables AGTB to be easily estimated, provided that diameter, total height, and wood specific gravity of a tree are available, irrespective of the tree species and of the location of the stand. The unit of the AGB estimated from the allometric equation is the kilogram (kg).

Details about testing and developing an allometric equation for estimating biomass are presented in Annex 6. The guidelines suggest the choice of the best predictive allometric equations (models) in estimating AGTB developed by Chave et al. (2005) on the basis of climate and forest stand types. Eq. (v) is good for moist forest stand, eq. (vi) for dry forest stand, and eq. (vii) for wet forest stand.

$$AGTB = 0.0509 * \rho D^2 H \qquad \text{…… eq. (v)}$$
$$AGTB = 0.112 * (\rho D^2 H)^{0.916} \qquad \text{…… eq. (vi)}$$
$$AGTB = 0.0776 * (\rho D^2 H)^{0.940} \qquad \text{…… eq. (vii)}$$

where,

$AGTB$ = above-ground tree biomass [kg];

ρ = wood specific gravity [g cm^{-3}];

D = tree diameter at breast height [cm]; and

H = tree height [m].

After taking the sum of all the individual weights (in kg) of a sampling plot and dividing it by the area of a sampling plot (250 m^2), the biomass stock density is attained in kg m^{-2}. This value can be converted to t ha^{-1} by multiplying it by 10. Since the pilot areas are part of the tropical and sub-tropical region, the biomass stock density of a sampling plot will be converted to carbon stock densities after multiplication with the IPCC (2006) default carbon fraction of 0.47.

6.2 Above-ground sapling biomass (AGSB)

To determine the above-ground sapling biomass (AGSB) (<5cm DBH), national allometric biomass tables can be used. These tables are developed by the Department of Forest Research and Survey (DFRS) and the Department of Forest, Tree Improvement, and Silviculture Component (TISC) (Tamrakar 2000). Since the national allometric biomass table does not contain all species present in Nepal, values for related or similar species may be used. The biomass values of saplings include foliage, branch, and stem compartments. The following regression model is used for an assortment of species to calculate biomass.

$$\log(AGSB) = a + b\, log(D) \quad \text{…………………………………… eq. (viii)}$$

where,

$\log$ = natural log [dimensionless];

$AGSB$ = above-ground sapling biomass [kg];

a = intercept of allometric relationship for saplings [dimensionless];

b = slope allometric relationship for saplings [dimensionless]; and

D = over bark diameter at breast height (measured at 1.3 m above ground) [cm].

Biomass stock densities are converted to carbon stock densities using the IPCC (2006) default carbon fraction of 0.47.

6.3 Leaf litter, herb, and grass (LHG) biomass

To determine the biomass of leaf litter, herbs, and grass (LHG), samples are taken destructively in the field within a small area of 1 m^2. Fresh samples are weighed in the field with a 0.1 g precision; and a well-mixed sub-sample is then placed in a marked bag. The sub-sample is used to determine an oven-dry-to-wet mass ratio that is used to convert the total wet mass to oven-dry mass. A sub-sample is taken to the laboratory and oven dried until constant weight to determine water content. For the forest floor (herbs, grass, and litter), the amount of biomass per unit area is given by:

$$LHG = \frac{w_{field}}{A} \cdot \frac{w_{subsample,dry}}{w_{subsample,wet}} \times \frac{1}{10000} \qquad \text{.. eq. (ix)}$$

where,

LHG	=	biomass of leaf litter, herbs, and grass [t ha^{-1}];
w_{field}	=	weight of the fresh field sample of leaf litter, herbs, and grass, destructively sampled within an area of size A [g];
A	=	size of the area in which leaf litter, herbs, and grass were collected [ha];
$w_{subample,dry}$	=	weight of the oven-dry sub-sample of leaf litter, herbs, and grass taken to the laboratory to determine moisture content [g]; and
$w_{subsample,wet}$	=	weight of the fresh sub-sample of leaf litter, herbs, and grass taken to the laboratory to determine moisture content [g].

The carbon content in LHG, $C(LHG)$, is calculated by multiplying LHG with the IPCC (2006) default carbon fraction of 0.47.

6.4 Soil organic carbon (SOC)

Soil samples are collected at 0-10, 10-20, and 20-30 cm depths. Samples of exactly 100 cm^3 are taken and transferred to pre-weighed sampling bags. Wet weights of soils are determined in the field with 0.1 g precision. Subsequently, samples are transported to the laboratory and oven dried (70^{0} C) until constant weight to determine water content. Samples from each of the three depths are composted and well-mixed per sampling plot and then prepared for carbon measurement by removing stones and plant residue > 2mm as well as by grinding. The carbon stock density of soil organic carbon is calculated as (Pearson et. al 2007):

$$SOC = \rho \times d \times \%C \qquad \text{.. eq. (x)}$$

where,

SOC	=	soil organic carbon stock per unit area [t ha^{-1}],
ρ	=	soil bulk density [g cm^{-3}],
d	=	the total depth at which the sample was taken [cm], and
$\%C$	=	carbon concentration [%].

6.5 Below-ground biomass (BB)

One of the most common descriptors of the relationship between root (below-ground) and shoot (above-ground) biomass is the root-to-shoot ratio, which has become the standard method for estimating root biomass from the more easily measured shoot biomass. Below-ground biomass estimation is much more difficult and time consuming than estimating above-ground biomass. Measurements of root biomass are indeed highly uncertain, and the lack of empirical values for this type of biomass has for decades been a major weakness in ecosystem models (Geider et al. 2001). To simplify the process for estimating below-ground biomass, it is recommended that MacDicken (1997) root-to-shoot ratio value of 1:5 is used; that is, to estimate below-ground biomass as 20% of above-ground tree biomass.

6.6 Total carbon stock density

The carbon stock density is calculated by summing the carbon stock densities of the individual carbon pools of that stratum using the following formula. It should be noted that any individual carbon pool of the given formula can be ignored if it does not contribute significantly to the total carbon stock.

Carbon stock density of a stratum:

$$C(LU) = C(AGTB) + C(AGSB) + C(BB) + C(LHG) + C(DWS) + SOC \quad \text{………………… eq. (xi)}$$

where,

$C(LU)$	=	carbon stock density for a land-use category [Mg C ha^{-1}],
$C(AGTB)$	=	carbon in above-ground tree biomass [Mg C ha^{-1}],
$C(AGTB)$	=	carbon in above-ground sapling biomass [Mg C ha^{-1}],
$C(BB)$	=	carbon in below-ground biomass [Mg C ha^{-1}],
$C(LHG)$	=	carbon in litter, herb & grass [Mg C ha^{-1}],
$C(DWS)$	=	carbon in dead wood and stumps [Mg C ha^{-1}], and
SOC	=	soil organic carbon [Mg C ha^{-1}]

The total carbon stock is then converted to tons of CO_2 equivalent by multiplying it by 44/12, or 3.67 (Pearson et al. 2007).

Chapter seven: Leakage analysis

Leakage is defined as an increase in greenhouse gas (GHG) emissions outside of the project area but directly attributable to the REDD project activities implemented inside of the project area. A distinction is made between primary leakage, when the emissions are directly attributable to the deforestation agents, and secondary leakage when the emissions are not directly attributable to the deforestation agents but rather to other actors through effects on prices and markets (Aukland et al. 2003). This document focuses on activity-shifting leakage.

Any activity that reduces deforestation within a certain area may increase deforestation in an area outside of the project area. For example, the protection of forest land from grazing inside the project area can lead to the conversion of forest land into grazing land outside the project area. Similarly, closing down a forest for the collection of fuelwood can increase fuelwood collection in the immediate vicinity of the project area. A third example relates to logging: if under the baseline scenario logging was occurring within the project area, project actions can lead to displacement outside of the project area. The existence of leakage reduces the GHG benefits from increases in forest stocks or reductions in deforestation. Mitigating and preventing leakage is crucial for ensuring that REDD and forest projects actually reduce carbon emissions.

Leakage is caused because a forest resource, such as timber, fodder, or firewood, is not available anymore in the protected area without direct substitution. Therefore, leakage can be minimized by (1) reducing the consumption of this resource through more efficient use, (2) continuing to harvest the resource in the protected forest but in a sustainable way, or (3) providing a substitute for the resource such as substituting fodder collected in the forest by grass collected outside the forest.

In other words, the potential for leakage is directly related to the difference between resource consumption (RC) and resource extraction (RE). The RE can originate from community-based forests engaged in the REDD program, an individual’s agricultural land, or private uncultivated land. If RC=RE, all the resources that are consumed can be produced within the community forests or on agricultural land and there is no possibility of leakage.

Leakage can be quantified by monitoring deforestation, forest degradation rates, and resource consumption in leakage belts, i.e., the area adjacent to the project area. The size and location of the leakage belts can be identified beforehand by GIS analysis.

7.1 Determining the size and location of the leakage belts

Local communities are the main agents of deforestation. Therefore, leakages will remain close to the project areas. The geographical area in which leakages are monitored must be determined and fixed before the project starts. A correct demarcation of each leakage belt is crucial to account accurately for the GHG benefits of the REDD project since it is an area where leakages will be monitored and deducted from the actual NERs. The size and location of the leakage belts are determined using a cost-of-transportation-based GIS approach and participatory rural appraisals. The following steps are followed.

- Determine the average 'cost' to move across a forest stratum, landscape class, or road and/or track. The relative costs must be calculated by reciprocating the maximum speed for every class or road category and the relevant mode of transportation. The costs therefore represent the fastest time it takes to cross a set distance.
- Using a GIS, a raster map of the watershed is created in which every grid cell contains the cost to cross this pixel based on the class or roads and/or tracks that are present within the cell. The cost to cross areas that are not accessible to deforestation agents must be set to an arbitrary large value. Examples of inaccessible areas include protected areas, national parks, economic land concessions, and large plantations.
- Using the cost map, generate a cost-distance map of the watershed in which every grid cell contains the cost (time) to reach the nearest point of the community forest areas that are participating in the REDD program.
- For every agent of deforestation and/or degradation, estimate the extra time this agent is willing to take to move their deforestation activities from the project area to the nearest accessible forest.
- Select the area in the cost-distance map that is accessible from the boundary of the project area within the maximum time determined in the previous step. Therefore, when different agents and drivers of deforestation are active, the **most mobile deforestation agent** shall determine the size of a leakage belt. Note that the leakage area should be fully encompassed within the reference region. Increase the size of the reference region if necessary to accommodate the leakage belts defined.

7.2 Leakage monitoring

Certain variables are monitored within the project area and leakage belts during project implementation:

- **The number of head loads of firewood and fodder** extracted from the forest will be counted for 3-4 consecutive days in each collection period. Counts should be carried out separately for male adults, female adults, and children younger than 13 years.

- **The weight of the head loads** is determined per category and season.
- **The number of domestic animals, the related fodder requirements, the grazing period, the amount of crop residue fed to animals, and the firewood consumption** are determined through questionnaires. Around 20-30% of the households representing all social categories should be interviewed every collection season.
- **The daily fodder consumption** is measured by isolating 3-5 individuals in a stall and weighing the fodder consumed by them. The moisture content of the fodder is determined separately by comparing the moist weight of a sample with the weight of the sample after oven drying. Separate measurements are taken for different livestock species such as cows, buffalos, and others. Fodder consumption is measured in 3-4 different seasons.

7.3 Leakage reduction measures

A number of measures can be implemented to reduce the potential for leakage.

- Fodder production can be established on open land which has no forest or woody biomass.
- Existing and new fodder production can be optimized through improved sowing, fire control, and by avoiding the collection of fodder before plants reach maturity.
- Community members can be educated on the importance of not using tree leaves as fodder due to their adverse effect on animal growth.
- Priority can be given to collecting fallen wood from forests for timber and fuelwood so that the pressure on live trees is minimized.
- Woodlots in which firewood species are growing can be established next to crop fields and homesteads.
- Fuel-efficient, improved wood-burning stoves and bio-gas digester plants can be promoted.
- The total number of trees and households can be counted to calculate the availability of tree resources per household. The rate of sequestration may vary because of these factors.

All the measures the communities take to conserve the forest are recorded during community meetings.

Chapter eight: Quality assurance and quality control (QA/QC)

Provisions for quality assurance (QA) and quality control (QC) must be implemented to ensure that the carbon stocks and credits reported are reliable and meet minimum measurement standards. The QA/QC provisions are an integral part of standard operation procedures and include procedures for: (1) collecting reliable field measurements; (2) verifying laboratory procedures; (3) verifying data entry and analysis techniques; (4) checking data completeness and consistency; and (5) maintaining and archiving data.

8.1 Field measurements

Rigorous standard operating procedures (guidelines) must be developed to detail all steps taken in the field. Guidelines ensure that measurements executed by different teams or at different times are consistent and comparable. Once the guidelines are developed, those responsible for carbon measurement must be trained extensively according to the guidelines so as to be fully cognizant of all procedures and the importance of collecting accurate data. During every field visit, a document should be produced and filed with documents proving that all steps from the guidelines have been followed: similarly, all deviations from the guidelines, if any, must be listed. The guidelines have to be updated officially if significant issues arise with the procedures.

An audit program for field measurement and sampling should be established. A typical audit program consists of three types of checks. During a *hot check*, auditors (technical experts) observe members of the field crew during data collection on a field plot (this is primarily for training purposes). *Cold checks* occur when field crews are not present for the audit. *Blind checks* represent the complete re-measurement of a plot by the auditors. Hot checks allow for the correction of errors in techniques, while blind checks allow for calculation of measurement variance.

When field work is completed, about 10% of the plots should be checked independently. Field data collected at this stage can be compared with the original data, and errors should be corrected and recorded. To provide an estimate of the measurement errors, errors can be expressed as a percentage of all plots that have been rechecked.

8.2 Laboratory measurements

Guidelines for laboratory measurements should be prepared by the laboratory staff and be followed for each part of the analysis. If an external laboratory performs the analysis, a record of the procedure(s) must be obtained. A typical crucial step for laboratory measurements is, for example, the calibration of combustion instruments for measuring total carbon or carbon forms using commercially available and certified carbon standards. Similarly, all balances for measuring dry weights should be calibrated periodically against known weights and fine-scale balances should be calibrated by the manufacturer. Where possible, 10 to 20 per cent of the samples should be re-analyzed and /or re-weighed to produce an error estimate.

8.3 Data entry

Data entry can be done immediately in the field using laptop computers. In most cases, however, measurements are written down in the field and must be entered manually on to spreadsheets and/or datasheets. Data entry on to spreadsheets and/or a database is often a significant source of error. Ongoing communication between all personnel involved in measuring and analyzing data is critical for resolving apparent anomalies before final analysis. Special attention must be paid to units used in the field. Typical mistakes are confusion between diameters or circumferences if trees are measured, or the length unit (mm, cm, and inches). All measurements contained in spreadsheets and/or datasheets must have their unit clearly indicated. Errors can be reduced by spot checks of the data entered by independent personnel. In addition, outliers can be identified by checking whether each value is within an expected range. If during spot checks or range checks a significant number of errors is found, all data must be re-checked by independent personnel. If there are anomalies that cannot be resolved, the plot should not be used in the analysis.

8.4 Data completeness and consistency check

To assist field inventory personal, data analysts and individuals and institutions involved in evaluating the quality of analytical data, quality assurance and quality control (QA/QC) procedures are developed. The QA/QC procedures include specific criteria to evaluate the quality of the analytical data that have been gathered. These QA/QC procedures will promote the acceptance of the analytical data in the marketplace for carbon credits and reduce the need for additional sampling and analysis to support and/or confirm the analytical data and the professional decisions. The QA/QC procedures are therefore an absolutely essential part of any sampling operation. These QA/QC procedures evaluate (a) data completeness and (b) data consistency.

a. Completeness check

One of the important steps related to QA/QC is to ensure that the data gathered are complete and stored correctly. A thorough evaluation of the data completeness should be carried out as soon as possible after the field work, so that missing data can be retrieved in a reasonable time.

- Completeness of files
  - Are all the digital pictures and electronic scans of the sample sheets available and named correctly?
  - Are digital pictures of the GPS screen indicating the position of a sampling plot available and named correctly?
  - Are all the scanned packages of each of the data sheets complete and in the correct order?

Once all the electronic data files are checked, the individual elements within the data files must be checked for completeness.

- Completeness of data within the electronic files
  - Data cover sheet
    - Are data for all the plots requested present?
    - Are all plot IDs named correctly?
    - Are all coordinates for the plot centers available?
    - Are preliminary inventory data and results reflecting sample design present?
    - Does the number of plots required in the preliminary inventory match the number of plots in the actual inventory?
  - Plot information
    - Are data present for all the plots requested?
    - Is a strata name/number given for each plot?
    - Is the naming convention of the plot ID followed?
  - Above-ground live trees
    - Are data present for all the plots requested?
    - Is the naming convention of the plot ID followed?
    - Are all tree species' names provided?
    - Are all tree tag numbers provided?
    - Are all DBH measurements greater than 5 cm?
    - Are there any unusually large DBH measurements?
  - Canopy cover percentage
    - Are data for all plots requested present?
    - Is the naming convention of the plot ID followed?
    - Are the total square counts equal to 24 per reading?

        - Are 4 separate readings per plot recorded?
    - Standing dead wood
        - Is the naming convention of the plot ID followed?
        - Are decomposition classes 1, 2, or 3 assigned to each standing dead tree?
    - Fallen dead wood
        - Is the naming convention of the plot ID followed?
        - Are decomposition classes 1, 2, or 3 assigned to each piece of dead wood?
    - Logged tree stumps
        - Is the naming convention of the plot ID followed?
        - Are all height/diameter readings present?
        - Are decomposition classes 1, 2, 3, or 4 assigned to each piece of dead wood?

b. Consistency check

The QA/QC procedures should ensure that the data measured are consistent throughout the scope of the project so that the same analytical approach can be implemented.

- Data cover sheet
    - In a spot check with the pictures showing the GPS coordinates on the GPS screens were at least 50 coordinates correct?
    - In a spot check with scanned datasheets were 10 randomly-selected values of coordinates correct?
    - If the plot was not indicated to be 'relocated', are the actual coordinates of the plot center equal to the coordinates requested?
      Calculate the distance between the actual plot center and relocated plot. This distance must be less than 20 m using the distance method; i.e.,

      $$D = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \text{.......................... eq. (xii)}$$

      where, *D is the distance in meter(s) between two plot centers, (X_2,Y_2) and (X_1,Y_1) UTM coordinate pairs of two plot centers.*
    - If the plot was indicated to be 'relocated', was the distance between the relocated and requested coordinates smaller than 300 m?
    - Is slope measurement for the plot realistic; i.e., within 0-60 degrees? (If over 60 degrees check the crown cover and tree density for possible error, since high crowns usually will give greater tree density in sloping terrain.)

- Above-ground live trees
  - Are all tree tags unique within one plot?
  - In a spot check with scanned datasheets were 10 randomly-selected values correct?
  - Are minimum and maximum of the DBH within each plot realistic?
  - Is the correct unit of measurement employed in all information recorded?
  - Are counts of trees within each plot realistic?
  - Is the biomass calculated per plot realistic? - Use any allometric equation available or any local literature on the region previously studied to spot the error and/or outliers.

- Canopy cover percentage
  - Are the number of sky squares + number of canopy squares everywhere equal to 24 for each plot?
  - Are there 4 densiometer measurements per plot?
  - Is the average canopy cover larger than 0 and smaller than 100?
  - In a spot check with scanned datasheets were 10 randomly selected values correct?
  - Is the correlation between canopy cover and above-ground live trees realistic? For example, in Figure 10, the circles are potential outliers for 10 randomly selected plots.

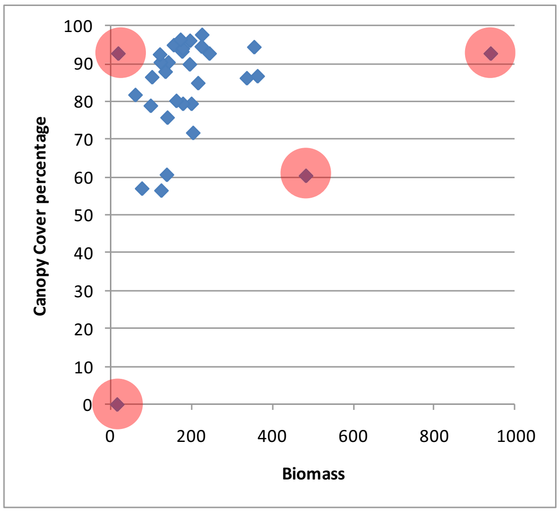


Figure 10: Correlation between canopy cover and tree biomass

- Standing dead wood
  - Conduct a spot check with scanned datasheets for 10 values
  - Are minimum and maximum of the DBH within each plot realistic?

  - Are the carbon density values calculated realistic?

- Downed dead wood
  - Conduct a spot check with scanned datasheets for 10 values
  - Are the minimum and maximum of the inner and outer DBH within each plot present and realistic?
  - Are the carbon density values calculated realistic?

- Logged tree stumps
  - Are the numbers of logged tree stumps recorded realistic given the tree density in the forest?
  - Conduct a spot check with scanned datasheets for 10 values?
  - Are the carbon density values calculated realistic?

- Data naming conventions

  Ensure that all database files are named correctly. The efficiency of data analysis as well as error checking can be enhanced by rigorously following a strict naming convention.

8.5 Data archiving

Because of the relatively long-term nature of forestry activities, data archiving and storage are important and should include the following steps.

- Original copies of the field measurement (data sheets or electronic files) and laboratory data should be maintained, entered in electronic media, and stored in a secure location.
- Copies of all data analyses, models, final estimates of the amount of carbon sequestered, GIS products, as well as a copy of the measuring and monitoring reports should all be stored in a secure location (preferably offsite).
- Given the period for reporting and the pace of production of software updates and of new hardware for storing data, electronic copies of the data and report should be updated periodically or converted to a format that can be accessed by new or updated software.

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Annex 1: Data sheet forms for a pilot inventory

Pilot Forest Survey Form (PFSF)

Date: / / 20 (day/month/year)

Site:

Preliminary stratum: **Pilot plot No.:**

Measurement conducted by:

Plot slope on average: (degrees) **Aspect:** **CFUG name:**

Easting: [m] (UTM x co-ordinate)

Northing: [m] (UTM y co-ordinate)

Altitude: [m] (above sea level) **Forest type:**

Key words describing the forest and terrain within and around the plot:

Examples: Dense, open, scattered trees, poorly stocked, plantation, multi-storey, newly thinned, heavily lopped, etc.

No.	Species	DBH [0.1 cm]	Comment	No.	Species	DBH [0.1 cm]	Comment
1		.		26		.	
2		.		27		.	
3		.		28		.	
4		.		29		.	
5		.		30		.	
6		.		31		.	
7		.		32		.	
8		.		33		.	
9		.		34		.	
10		.		35		.	
11		.		36		.	
12		.		37		.	
13		.		38		.	
14		.		39		.	
15		.		40		.	
16		.		41		.	
17		.		42		.	
18		.		43		.	
19		.		44		.	
20		.		45		.	
21		.		46		.	
22		.		47		.	
23		.		48		.	
24		.		49		.	
25		.		50		.	

Checklist:

* The plot is located pseudo-randomly (by pacing off the distance from the previous plot, road etc)

* Appropriate slope correction has been applied and measurements are done within a circular plot with a horizontal diameter of 8.92 m (area 250 sq.m.)

* All trees within the plot with DBH ≥ 5 cm have been measured

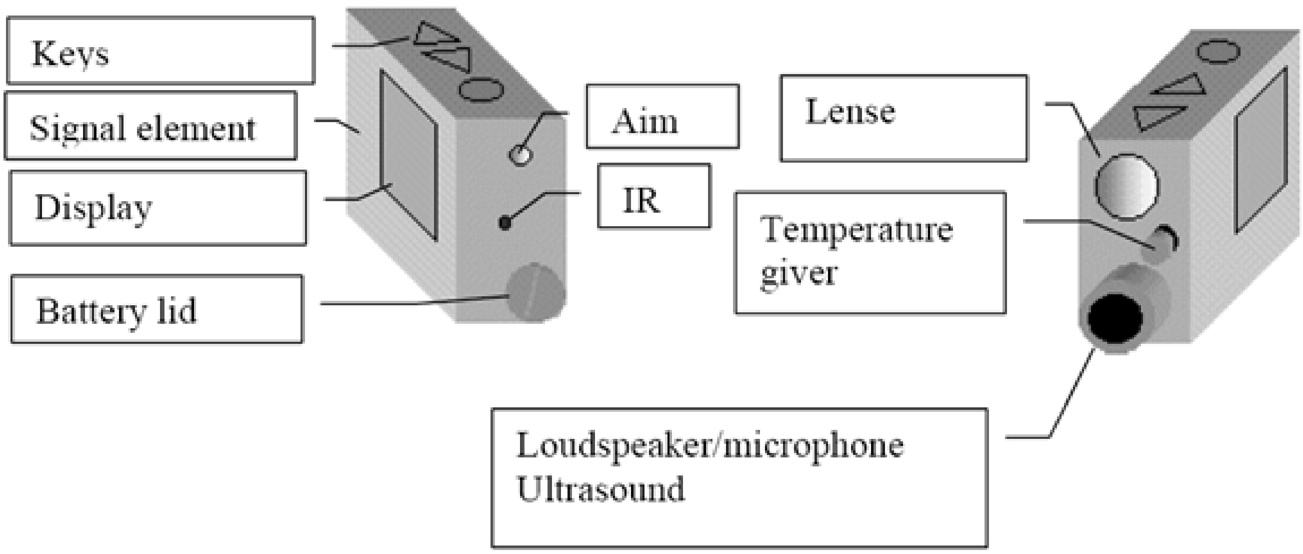
* The species of unidentified trees have been recorded as Sp 1...Sp 2 likewise and distinguishable characteristics are noted as comments

Annex 2: Description of equipment

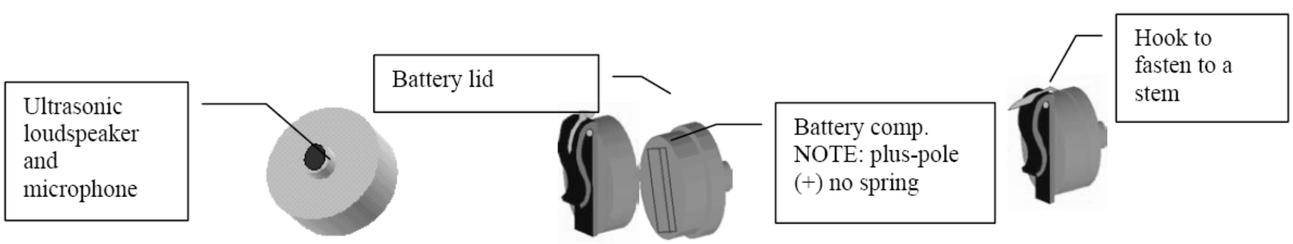
1. Vertex IV and Transponder T3 (Source: Vertex IV and Transponder, T3, manual January 2007, v.10)

1.1 Description

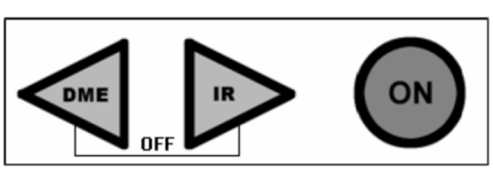
Vertex IV is primarily used to measure the height of standing trees. The instrument can also be used to measure distance, horizontal distance, angle, and inclination. The Vertex instrument uses an ultrasonic measuring technique for measurements.



To define a reference point in a secure and reliable way, the Vertex IV communicates and works with the transponder, T3.

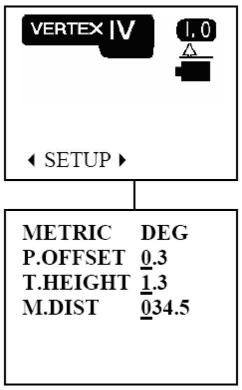


The Vertex IV has three keys: Two arrow keys and one ON key. To turn the Vertex IV off, press DME (distance measuring equipment) and IR (Infra red) keys together.



Vertex IV and the transponder, T3, each use an alkaline or a rechargeable battery of 1.5 V AA. The battery is placed under the battery cap, plus pole + down. Data in the Vertex can be sent through IR or Bluetooth.

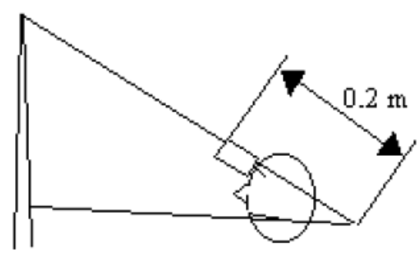
1.2 Setting-up the equipment



All settings to measure heights, distances, and angles are done with the SETUP menu. Choose between metric or feet, degrees or percentage, pivot offset, transponder height, and manual distance. Start Vertex IV by pressing ON. Press any of the arrow keys to go to the SETUP page and press ON to enter into the settings. Step to the parameter using ON and change values with the arrow keys.

METRIC/FEET Choose if the height and distance values should be featured in METRIC or FEET. Shift with the arrow keys and confirm your choice with ON.

DEG/GRAD/% Select the Angle unit as Deg (degrees 0 to 360), GRAD (gradients 0 to 400), or % (percentage) by pressing the arrow keys. Confirm by pressing ON.



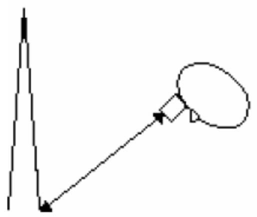
P.OFFSET (Pivot Offset) Change the value with the arrow keys and confirm your choice with ON. The value is shown in metric/feet.

The 'Pivot offset' is equal to the distance between the front side of the instrument to the point targeted where the prolonging of the sight line from the transponder and the top of the tree coincide. The imagined point is located somewhere behind your neck and the value should in normal cases be set to 0.3 m (1.0 feet).

Since the Vertex IV will presume that the transponder, T3, is placed directly under the targeted height of the measuring object (when the object is equal to a tree), a half of the object's diameter should be added to the Pivot Offset. This compensates for the diminishment of the tree top. When measuring tree heights, it is recommended to add half the average diameter in the area for improved accuracy.

T.HEIGHT (Transponder height)
Change the value with the arrow keys and confirm with ON. The value is set in metric/feet. T.HEIGHT is the height at which the transponder is set, the reference height for the measuring unit. The Vertex IV adds the preset T. HEIGHT to the height measured. Normal breast height value is set to 1.3 m (4.5 ft).

M.DIST (Manual distance)

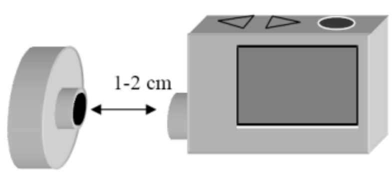


This function is useful when measuring without the transponder. Change the value with the arrow keys and confirm with the ON key. The value is shown in metric or feet. M. DIST is the manual distance to the reference point on the object where the height is measured. Make sure that the T.HEIGHT is correctly set, i.e., the height to the chosen reference point.

To perform any of the operations described below, ensure a battery is placed in the T3 properly and keep the measuring unit's loudspeaker towards the T3's loudspeaker.

1.3 Turning the T3 on and off

The T3 has no switch and the Vertex is used as a remote control to turn the T3 off and on. For turning the T3 both on and off, turn on the Vertex IV, press any of the arrow keys to go to the CALIBRATE page and press ON to enter into calibration and do as follows.



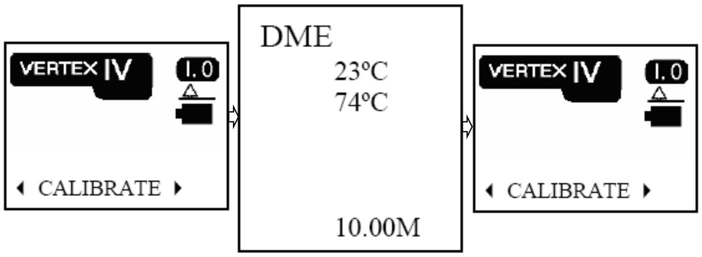
To turn T3 **ON**	Press ON until two signals beep from the T3.
To turn T3 **OFF**	Press ON until four signals beep from the T3.

The T3 is equipped with an audible signal that tells if the transponder is activated or not. Once turned on, the T3 Transponder stays activated for approximately 20 minutes.

1.4 Calibration

To increase and optimize the measuring accuracy, the instrument should be calibrated on a regular basis. The measuring fault can be made permanent if the instrument is calibrated before reaching the correct current temperature. Therefore, when calibrating, it is of utmost importance that the instrument has been given enough time to stabilize at ambient temperature.

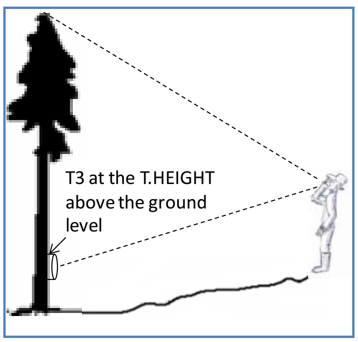
Use a measuring tape to measure the exact distance of 10 m (32.8 feet) between the T3 and the Vertex front.



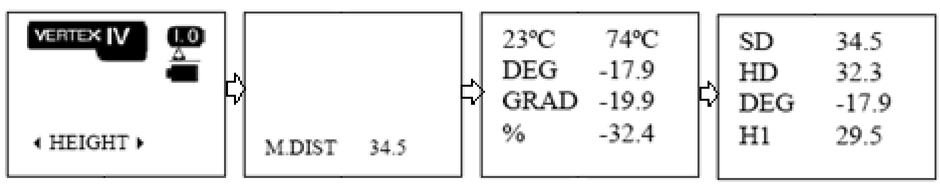
Press ON to start the Vertex instrument, step in the menu to CALIBRATE and press ON. The instrument will calibrate to 10 m, automatically exit from the calibration and display the CALIBRATE page.

<u>Again, it is important to give the instrument approximately 10 minutes to set to the correct temperature before calibrating.</u>

1.5 Measuring tree height with transponder, T3



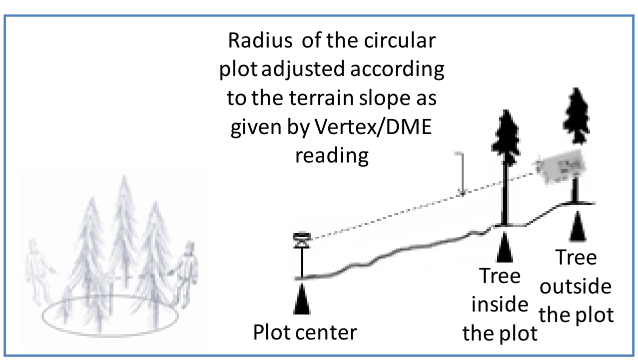
Start the transponder, T3, and place it on the tree to be measured. Note that the transponder should be placed at the T.HEIGHT (transponder height) that has been determined in the settings menu. Walk a suitable distance from the object – for optimal accuracy, a distance equal to the approximate tree height.



1. Press ON to start the Vertex, scroll to the HEIGHT page and aim at the transponder. Keep pressing ON until the cross hair sight goes out momentarily. Now release ON. The Vertex has measured the distance, the angle, and the horizontal distance to the transponder.

2. Aim at the height to measure with the sight cross blinking. Press ON until the cross hair disappears. The height of the tree is locked and displayed.

1.6 Detecting the trees on the edge (circumference) of a circular plot

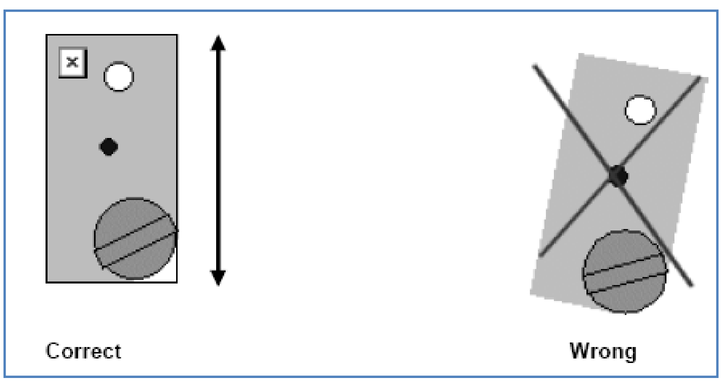


When the T3 is used with the adapter (graduated staff), the ultrasound is spread and it is possible to take measurements from any direction. This is particularly useful when working in circular plots where the distance from the plot center to trees within a defined circle should be measured.

To determine the radius in the case of a circular plot, first fix the T3 at T. HEIGHT at the center of the plot, then press the DME key (left arrow key) when the Vertex IV is turned off. The distance between Vertex IV and T3 is presented in the Vertex display. Now move away from the center until the distance reading on the Vertex equals the radius of the circular plot (in the case of sloping terrain, the radius should be adjusted according to the slope). As the Vertex gives a reading of the shortest distance, make sure you hold the Vertex at T.HEIGHT above ground level while taking a Vertex reading. Now you can determine whether the surrounding trees are within or outside the circular plot.

1.7 Important precautions to take while using Vertex IV

- Vertex IV uses ultrasonic signals to determine distances. Humidity, air pressure, surrounding noise, and, above all, the temperature can affect the range and extension of ultrasonic signals.
- In some cases, distances of 50 meters and greater can be measured without problems and, in other cases, the maximum distance can be shorter than 30 meters.
- Check your instrument daily and recalibrate it if necessary. Do not touch the temperature sensor at the front of the instrument (the metal knob between the sight and the loudspeaker) and never calibrate the instrument before it has reached ambient temperature.
- When measuring heights, it is important to hold the instrument as straight as possible.



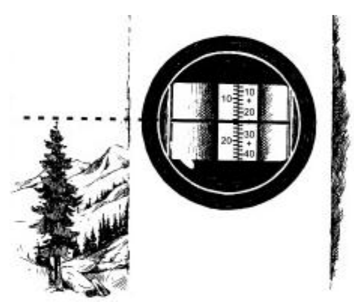
For further information and technical specifications of the sets of equipment, consult the user manual.

2. Silva survey master

2.1 Description

This patented double instrument is a combination of the Sight Master and the Clino Master and is especially well suited for professionals who need to measure vertical angles, heights, and compass bearings. Typical users of this kind of instrument are surveyors, geologists, speleologists, miners, satellite dish installers, engineers (telecom), and foresters. The Clino Master is used to measure angles/heights and the Sight Master is used to measure the bearings.

2.2 Measuring angles with Clino Master

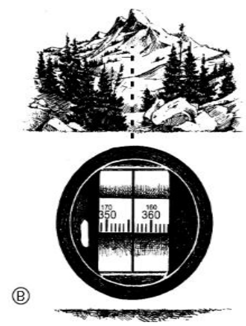


The Clino Master can be used to measure angle and direct distance. The following steps should be followed to do so.

- Place yourself at a suitable distance from the object, if possible a distance equal to the height of the tree.
- Hold the Clino Master vertically close to one of your eyes. Because of the optical illusion, the index line will appear to ’stand out’ from the Clino Master housing making it easy to read the correct angle.

- Sight with both eyes towards the top of the tree.
- Read the angle at the index line on the left side scale. The angle is given in degrees on the left side and in percentages on the right side. For example 15^{o} and XX%
- A similar process can be repeated when measuring the angle at the base of the tree.

2.3 Measuring the bearing using Sight Master



The Sight Master can be used in the following way to measure the bearing which is required when establishing reference points.

- Hold the compass horizontally in front of you, close to one of your eyes.
- Sight with both eyes towards the object. See Figure A
- You read the bearing through the compass sighting system at the same time you sight above the instrument towards the object. The index line will appear to 'stand up' from the compass housing making it easy to accurately read the correct bearing towards the object. See Figure B
- The bigger scale gives the bearing from your position to the object and the smaller one the reverse bearing from the object to your position. Reverse bearings are essential in accurate positioning tasks, particularly at sea.

2.4 Things to be considered while using Survey Master

The compass should be used as far as possible from iron and steel objects, such as engines, electrical equipment, knives, tools, and so forth, because they can cause magnetic interference and direction errors. Even wrist watches and steel-framed spectacles may cause deviation in the bearings.

3. Densiometer

3.1 Description

A spherical densiometer is a common yet simple instrument for measuring forest over-storey density or canopy cover (Figure 11). The instrument has a reflective spherical surface divided into 16 equally spaced square grids. When the instrument is taken under forest canopy, images of the overhead crown can be seen in the mirror and the amount of canopy coverage is estimated based on the proportion of the mirror surface reflecting the over-storey crown.

Figure 11: Spherical densiometer

3.2 Estimating canopy cover using a densiometer

Although it is ideal to take canopy cover measurements in each sample plot, depending on resources, canopy measurements can be taken in several plots. Plots where canopy measurements are taken, however, should be allocated in proportion to the area of different strata. Prior to taking canopy cover measurements, all trees should be tagged and diameters at breast height (DBH) measured. This measurement procedure can be handled efficiently by one person using the following procedure.

1. Hold the densiometer far enough away from your body so that your head is just outside the grid (30-45 cm away). Maintain the densiometer approximately at elbow height. Keep the densiometer instrument leveled, as indicated by the round level in the lower right hand corner.
2. Count the number of canopy opening squares. If there are squares that are only partially filled, these can be added to make a complete square. Note that there are 24 squares of 3 x 3 mm in the grid. Each square represents an area of canopy opening (sky image or unfilled squares) or canopy cover (vegetation image or filled squares). For deciduous trees in late autumn to winter, when trees have no leaves, the crown area needs to be

visualized for a proper reading. Only squares that are completely free of branches should be counted as sky.

3. Note down the total number of squares that are filled on the sampling sheet.
4. An average of four measurements must be taken for all plots. The four measurements must be taken 5m from the plot center in the North, East, South, and West (Figure 12).

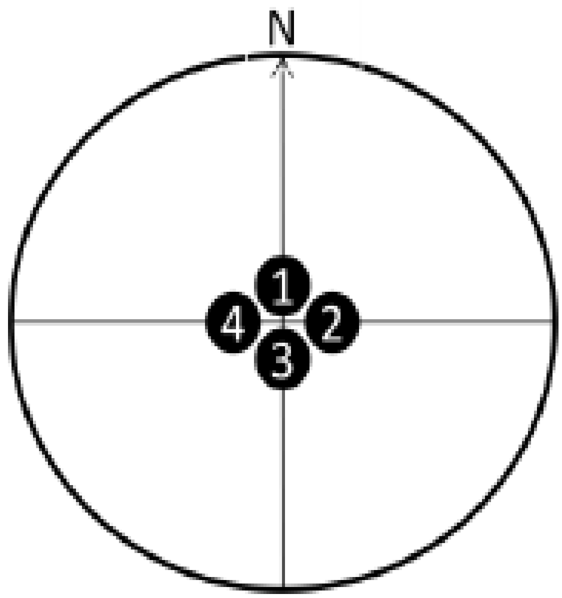


Figure 12: Position for taking densiometer measurements

The data sheet template is shown in Annex 3, Section 8. The average number of sky squares and canopy squares can be calculated during data analysis.

If a spherical densiometer is not available, a densiometer can be made using locally available materials. When resources permit, hemispherical photos using a digital camera with a fish eye lens such as FC E8 can be taken during the field inventory. The digital image can be analyzed then using a Gap Light Analyzer (GLA) (http://www.ecostudies.org/gla/) image analysis program (Frazer et al. 1999).

4. GPS enabled camera

Sound measurement of the coordinates of the sampling plot is essential for further analysis of the biomass. Given the importance of the accuracy of the coordinate measurement, it is highly recommended to include as much redundancy as possible for this measurement. For example, GPS-enabled cameras can be used to record the coordinates on to pictures of the surrounding area, the sample sheet, and the screen of the main GPS device. If during the data analysis or QA/QC process a discrepancy in plot location is observed, the image with the GPS coordinate embedded in it can be used to resolve the error.

1. Assemble at the plot center. Turn the first page of the detailed inventory form. Record the data as required on this form. Turn on the GPS equipment and allow it to acquire the coordinate location of the plot center. Place the GPS equipment on the plot center, and place the cover sheet of the data sheet package alongside. Take a picture of both the first sample sheet and the screen of the main GPS device showing the GPS coordinates with the GPS enabled camera. Record the time and date at which the picture is taken.
2. Once the picture is taken, it should be given a name in the following format of "plotname_picture". For example if the plot id is "plot123" then the picture file's name will be "plot123_picture.jpg" and this naming standard should be maintained.
3. Once the field crew returns to office, these picture files should be downloaded and stored in the existing Access database file in the table that describes plot-level information. GPS-enabled cameras store the GPS coordinates in the EXIF header of a digital picture file. The GPS coordinates can be retrieved using the free 'exiftool' program available at http://www.sno.phy.queensu.ca/~phil/exiftool/.
4. In order to ensure that that the plot location is error free, the distance between the measured plot center and the GPS coordinates recorded by the GPS-enabled cameras can be calculated. A big distance indicates a potential error, keeping in mind that some distance will be present since the accuracy of GPS-enabled cameras is much less than the accuracy of the main GPS instrument. A simple scatter diagram of X and Y coordinates of the plot centers taken with the main GPS instrument vs. the GPS-enabled camera can also be used to check for potential errors.

Annex 3: Datasheet form for detailed forest carbon inventory

Carbon Stock Measurement Form (CSMF)

Plot No.: ______
Strata: ______
District:

Measurement started at: ______ (time, e.g., hour : minute)
Date: ___ / ___ /2010 (dd/mm/yy)
Team leader: ______
Team members: ______

Rough sketch showing the plot:

References for the plot center:

1. Background information

CFUG Name: ______
Forest Name: ______
Block number: ______

GPS co-ordinates
UTM-X ______ m
UTM-Y ______ m
Altitude ______ m

2. Plot information

Please circle one

Forest type:	natural / plantation
Aspect:	N, S, E, W, NE, NW, SE, SW, Flat
Soil type:	clayey, loam, sandy, boulder
Fire:	Yes / No
Fodder collection:	Yes / No
Grazing:	Yes / No
Fuelwood collection:	Yes / No
Timber harvesting:	Yes / No
Encroachment:	Yes / No
Wildlife:	Yes / No
Soil erosion:	Yes / No

Please give a brief reason why if the plot has been relocated from the originally given GPS position.

Vegetation type:	
Slope:	degree (average)
Soil color:	
Soil depth:	m
Crown cover:	%
Shrub cover:	%
Grass cover:	%

Any additional information

Page 1 of 5

District:	Strata:	Plot No.:

3. Form for herbs and grass, litter, and soil samples

1. **Herbs and grass** - measure within a 0.56m core circular plot (all vegetation below 5DBH diameter)

total weight of all herbs and grass			weight of sample grass			number on the sample packet
		gram			gram	
bag	cloth	plastic	bag	cloth	plastic	

2. **Litter** - measure within a 0.56m core circular plot

total weight of all litter			weight of sample litter			number on the sample packet
		gram			gram	
bag	cloth	plastic	bag	cloth	plastic	

3. **Soil** - measure within a 1m circular plot

Depth			Composite soil sample (for carbon)
0 cm - 10 cm	0 cm – 10 cm	sample no.	total weight of the soil: gram (bag: white plastic / black plastic)
10 cm - 20 cm	10 cm – 20 cm	sample no.	number on the sample packet
20 cm - 30 cm	20 cm – 30 cm	sample no.	

4. Regeneration (below 1 cm DBH) - measure within a 1 m circular plot

SN	Species	Total count	SN	Species	Total count
1			6		
2			7		
3			8		
4			9		
5			10		

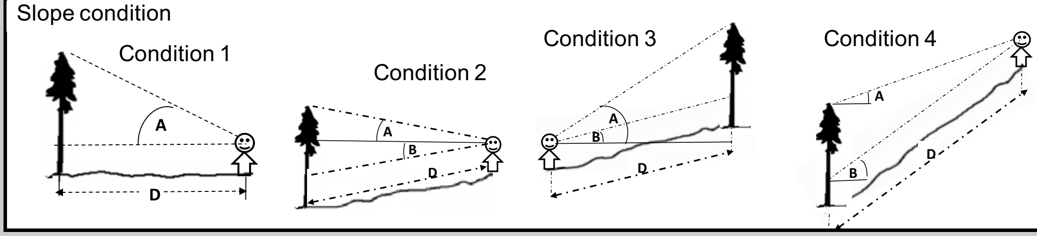
5. Sapling (1 cm to 5 cm) - measure within 5.64 m circular plot

SN	Species	DBH (cm)	SN	Species	DBH (cm)
1		.	11		.
2		.	12		.
3		.	13		.
4		.	14		.
5		.	15		.
6		.	16		.
7		.	17		.
8		.	18		.
9		.	19		.
10		.	20		.

Page 2 of 5

6. Tree - DBH and height measurements	District:	Strata:	Plot No.:

Slope condition



SN	Fork? a,b…	Species	DBH (cm) measured at breast height (1.3m)	Angles formed by top and base of the tree: top (**A**)	base (**B**)	Distance to the tree (m) (**D**)	Slope condition (see figure above)	Tree height (m)	Remarks
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	
			.	0	0	.		.	

*** Appropriate slope correction has been applied and measurements are done within circular plot with horizontal diameter 8.92 m (area 250 sq.m.)**

*** All trees within the plot with DBH ≥ 5 cm have been measured**

*** The species of unidentified trees have been recorded as Sp 1...Sp 2 likewise and distinguishable characteristics are noted as comment**

Page 3 of 5

7. Dead wood measurement form (DMF)

District: ______ Strata: ______ Plot No.: ______

	Logged tree			Standing dead wood			Down and dead wood									
Serial number	Tree stump height (cm)	Tree stump dia. (cm)	Decay class (1, 2, or 3)*	Height (cm)	DBH (cm)	Decay class (1, 2, 3, or 4)**	Length (cm)	Decay class (1, 2, 3, or 4)**	Maximum dia. (cm)	Section 1 mid dia. (cm)	Section 2 mid dia. (cm)	Section 2 mid dia. (cm)	Section 3 mid dia. (cm)	Section 4 mid dia. (cm)	Minimum dia. (cm)	Remarks

*Decay classes for logged tree

CLASS 1: Sound wood; a machete cannot sink into the wood in a single strike
CLASS 2: Intermediate wood; a machete sinks partly into the piece in a single strike
CLASS 3: Rotten/crumbly wood; a machete cuts through the piece in a single strike

**Decay classes for standing dead wood, down and dead wood

CLASS 1: With branches and twigs but without leaves
CLASS 2: With no twigs, but with small and large branches
CLASS 3: With large branches only
CLASS 4: Bole (trunk) only, no branches

8. Densiometer measurement form (DeMF)					District:		Strata:		Plot No.:	
	North		East		South		West		Average	
Grid cell	Number of Sky squares	Number of Canopy squares	Number of Sky squares	Number of Canopy squares	Number of Sky squares	Number of Canopy squares	Number of Sky squares	Number of Canopy squares	Number of Sky squares	Number of Canopy squares
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										

Consistency and completeness
It is verified that records on these forms are based on the real field measurements carried out according to the standard carbon measurement guidelines and all records are complete and consistent.
Name: Signature: Measurement end time:

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Annex 4: Random table

Random angles (0 - 360 degrees) used when relocating plots

First time: start in a random column and row. After use, cross out the chosen value.

Next time: use the value to the right of the previous one (move to the next line if necessary)

Go approx. 50m and establish the center of the plot.

337	211	76	299	272	52	318	27	77
78	243	262	145	117	247	206	309	347
337	329	137	241	218	269	249	81	324
20	182	93	133	94	135	118	14	324
300	301	155	77	137	53	143	229	320
17	211	136	340	226	335	310	49	252
82	111	351	6	13	91	276	316	205
237	38	5	65	256	261	193	68	332
160	356	275	81	64	247	304	184	190
83	34	85	61	89	43	91	259	124
34	205	207	115	245	250	281	346	323
332	39	157	123	272	265	19	125	154
14	102	260	134	200	92	150	108	144
228	227	47	31	352	21	103	1	229
62	293	189	25	344	23	130	15	257
85	3	56	44	351	188	195	318	101
29	38	299	68	209	315	194	142	4
332	321	188	173	134	269	193	55	318
337	230	57	82	269	308	149	78	66
37	304	303	3	349	96	179	125	327
27	88	85	264	296	145	48	130	115
35	10	176	334	173	123	330	300	121
205	230	137	324	301	358	276	241	237
190	333	231	323	7	238	15	69	162
190	258	43	208	339	327	351	223	317
323	214	75	351	333	184	275	357	284
101	32	262	77	311	39	167	129	156
239	38	90	39	35	304	248	127	16
13	126	298	206	223	294	339	123	28
191	32	86	90	94	38	210	185	148
178	243	289	116	138	126	6	13	350
139	0	323	203	286	217	185	121	353
101	9	130	11	33	353	38	257	305
169	358	136	316	267	112	321	301	49
181	104	242	108	355	248	330	244	159
191	124	356	49	140	35	200	271	295
42	156	281	29	86	181	275	332	293
128	65	240	349	86	262	307	225	137
183	47	181	90	228	204	261	209	65
313	54	90	115	166	208	358	64	108
262	87	118	287	173	300	290	95	81
306	45	274	279	11	336	121	36	347
201	250	36	17	215	22	125	88	266
126	179	35	243	359	181	312	335	307
346	320	277	41	275	127	226	34	88
301	104	259	203	21	137	115	213	234

Annex 5: Slope correction chart

Slope correction for the radius of the circle

Slope (degrees)	0.56m Herb/shrub/litter /soil	1m Seedling	5.64m Sapling	8.92m Tree
0	0.56	1.00	5.64	8.92
2	0.56	1.00	5.64	8.93
4	0.56	1.00	5.65	8.94
6	0.56	1.01	5.67	8.97
8	0.57	1.01	5.70	9.01
10	0.57	1.02	5.73	9.06
12	0.57	1.02	5.77	9.12
14	0.58	1.03	5.81	9.19
16	0.58	1.04	5.87	9.28
18	0.59	1.05	5.93	9.38
20	0.60	1.06	6.00	9.49
22	0.60	1.08	6.08	9.62
24	0.61	1.09	6.17	9.76
26	0.62	1.11	6.28	9.93
28	0.63	1.13	6.39	10.10
30	0.65	1.15	6.51	10.30
32	0.66	1.18	6.65	10.52
34	0.68	1.21	6.80	10.76
36	0.69	1.24	6.97	11.03
38	0.71	1.27	7.16	11.32
40	0.73	1.31	7.36	11.65
42	0.75	1.35	7.59	12.01
44	0.78	1.39	7.84	12.40
46	0.81	1.44	8.12	12.85
48	0.84	1.50	8.43	13.34
50	0.87	1.56	8.78	13.88

Annex 6: Testing and developing an allometric equation for estimating tree biomass

Before a specific allometric equation is used, it is good practice to test whether the equation can be applied by taking a small number of empirical measurements and comparing the predicted outcome with the measured outcome. A few allometric equations between DBH and/or tree height and biomass have been developed or tested for Nepal (Tamkrakar 2000). How well an allometric equation already established fits new observations can be tested using a reduced Chi-Square goodness-of-fit test. This test examines whether the variability between predicted biomass values and true biomass values is equal to the 'natural' variability in biomass values.

$$\chi_v^2 = \frac{1}{n-p-1}\sum_{i=1}^{n}\frac{\left(y_i - f_{allo}(DBH_i, height_i)\right)^2}{\sigma_i^2} \text{ ....eq. (xiii)}$$

where,

χ_v^2	=	reduced chi square;
n	=	number of measurements taken in the field to test the established allometric equation;
p	=	number of parameters used in the allometric equation (i.e., 1 if only DBH is used and 2 if both DBH and height are used);
y_i	=	empirically determined biomass of the tree, i;
f_{allo}	=	the established allometric equation that is to be tested;
DBH_i	=	the DBH of the tree, i;
$height_i$	=	the height of the tree, i; and
σ_i^2	=	the empirically determined variance of the biomass of the tree, i.

The allometric model is appropriate and assumed to be a 'good fit' when the reduced chi-square equals (or is close to) one. Allometric models that are not appropriate will yield reduced chi-square values greater than one. It can be demonstrated that for reduced chi-square values greater than 1.5, the allometric model is not appropriate at a probability level of 0.001[1]. This test requires that the variance of the biomass is known for a measurement. The variance can only be determined, in practice, by determining the biomass of a number of trees with equal DBH and/or height.

[1] http://neutrons.ornl.gov/workshops/sns_hfir_users/posters/Laub_Chi-Square_Data_Fitting.pdf

The following procedure can be used to execute the goodness-of-fit test.

1. Select the most appropriate allometric equations for the closest geographic location and/or tree species' groups in Nepal. These allometric equations may be similar among regions.
2. For each of the equations, select the smallest and largest DBH and/or height that are expected to occur within each of the regions in which the equation will be used.
3. Within the range determined by the smallest and largest DBH and/or height, select 8 DBH/height combinations according to the number of trees per DBH and/or height range. In other words, if most trees have relatively small DBH, select most of the 8 DBH/height combinations within the small DBH area (Figure 13).

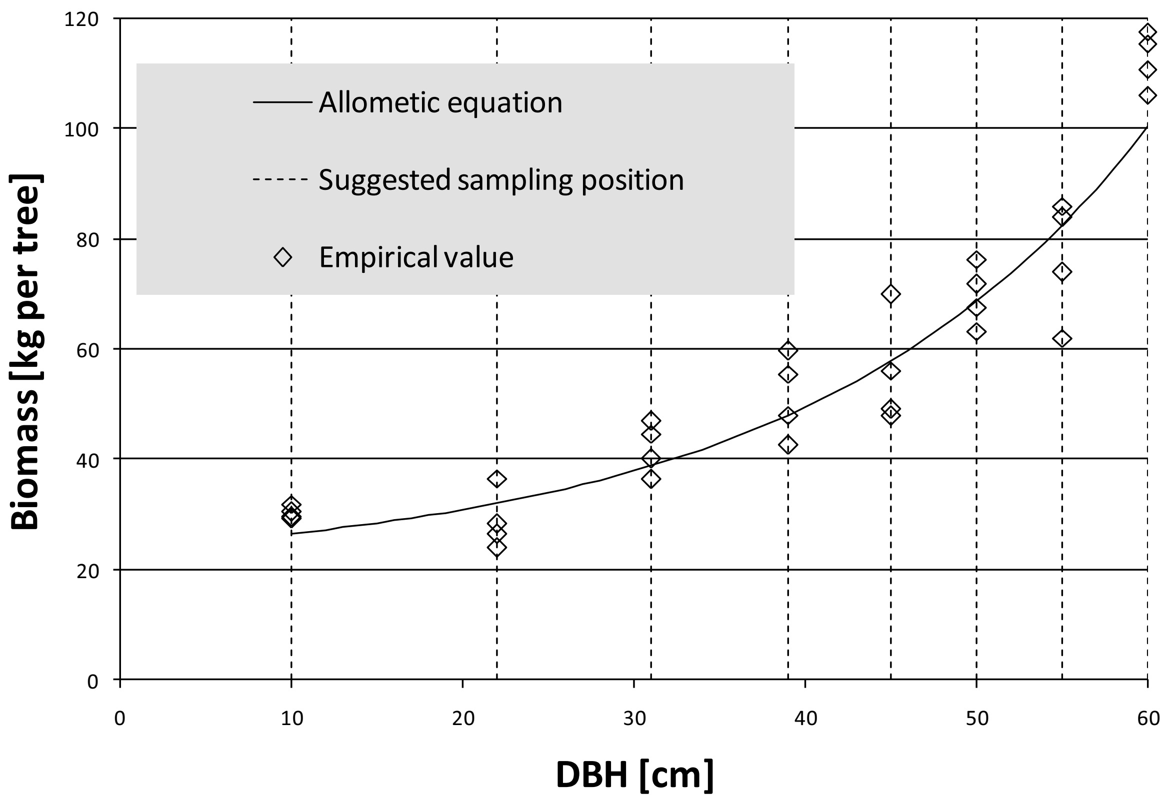

Figure 13: Example of selection procedure for trees to test the allometric equation.

4. Within the region for which the allometric equation is assumed to be representative, measure the weight of 4 trees for each of the 8 DBH/height combinations selected in the previous step. As a consequence, there will be 32 biomass measurements for every allometric equation.
5. Calculate the variance for each of the 8 DBH tree classes.

6. Construct a table with each of the 32 biomass measurements, the exact DBH and height, and the empirically determined variance for the relevant DBH tree class.
7. Calculate the reduced chi square metric using the equation above. If the value of the reduced chi square statistic is below 1.5, the allometric equation can be used. If the value is above 1.5, the allometric equation may not be appropriate. In the latter case, consider the following.
    - Taking more biomass measurements
    - Testing a different allometric equation
    - Splitting the region into more homogeneous smaller regions for which allometric equations will be appropriate
    - Estimating new parameters for the allometric equation selected
    - Developing a new allometric equation

The biomass of above-ground trees must be measured to test allometric equations developed previously or to develop new allometric equations. The following procedure can be used to measure the biomass of standing trees.

1. Record the DBH and/or height of a standing tree using diameter tapes and a hypsometer or clinometers, respectively.
2. Fell the tree and measure the diameters at the base and at 0.5, 1.0, 1.3, 2.0 m and every meter thereafter up to the top of the tree from the base.
3. Measure the tree's height up to the 0.1 m in accuracy, directly on the main stem.
4. Separate the tree into the individual components: (1) leaves and branches, (2) bole (trunk), and (3) roots, if any roots are present on the felled tree. Buck trunks to minimum commercial length (around 2.50 m) for further commercial use.
5. Weigh all leaves and branches, logs, and roots in the field. Use an electronic balance to an accuracy of 1g for material weighing less than 5 kg, and a separate balance of 50 g accuracy for heavier material.
6. Take sub-samples of each fresh tree component (minimally 250 g) and weigh the sub-sample in the field. Oven dry the sample in the laboratory to constant weight at 105°C temperature and record dry weights to 1 g of accuracy. Calculate moisture contents for each sample of each component.
7. Multiply total fresh weights of each biomass component with the one minus the moisture content to calculate the total dry biomass of each component of the tree.

If no allometric equation developed previously is found to be appropriate, a new set of allometric equation(s) should to be developed. The new allometric equation can be developed by estimating new parameters for the existing model or developing a completely new model.

1. Using a diameter distribution from forest inventories within the region of interest, select around 200 trees covering all the diameter classes in the forest.
2. From the 200 trees, determine how many per class have already been sampled for testing the goodness-of-fit of existing allometric equations. Subtract the number that has already been sampled from the total number of trees required per diameter class, which is the number of new trees required for measurement to develop a new allometric equation.
3. Measure the biomass of the required number of trees in the field using the procedure in the previous section.
4. Select a group of model forms for allometric equations. Common model forms in biomass studies are non-linear in nature. See Tamrakar (2000) for some models from Nepal.
5. Attempt to fit the data into selected model forms and evaluate the model to select the best. Selecting a model fit may also involve selecting a model developed previously or developing a new model. The evaluation process includes comparing different models using some subjective as well as statistical criteria. The first evaluation process is to see if the model and associated parameters are significant and this can be obtained from the non-linear model development procedures.
6. Models and parameters having statistical significance are primary candidates for further selection. The next step is to draw a scatter diagram to evaluate the residuals. Evaluations will be based on the position and trends of residuals. If there is a trend, then the model is accumulating error in some direction and that issue will have to be addressed or caution taken in using the output in that range.
7. Finally, the following quantitative criteria can be used to evaluate the models developed.

   a. Sum of residuals (smaller the better) $=\sum(w-\hat{w})$...........eq. (xiv)

   b. Average bias (smaller the better) $=\frac{\sum(w-\hat{w})}{n}$ ....eq. (xv)

   c. Sum of square of residuals (smaller the better) $=\sum(w-\hat{w})^2$..............eq. (xvi)

d. Standard errors of estimate (SSE) $=\frac{\sum(w-\widehat{w})^2}{n-k}$..................eq. (xvii)

e. Fit Index (FI) (larger the better) $=1-\frac{RSS}{TSS}$...................eq. (xviii)

Where, w is the measured weight, $\widehat{w}$ is the estimated weight, n is the number of observations, k is the number of estimated parameters, RSS is the residual sum of squares, and TSS is the total sum of squares.

8. If the above steps cannot be achieved or yield unreliable results, then use one of the equations described in Chave et al. (2005) as described in Section 6.1.