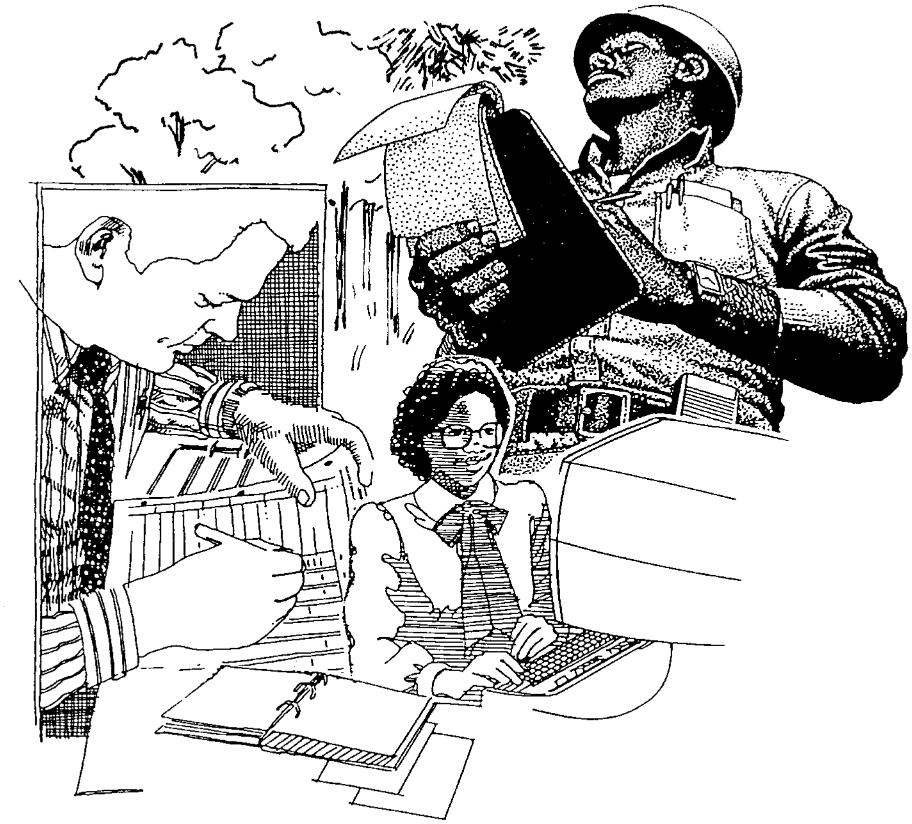
A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects



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Forest Carbon Monitoring Program

Winrock International Institute
for Agricultural Development

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Summary

As the international Joint Implementation (JI) program develops a system for trading carbon credits to offset greenhouse gas emissions, project managers need a reliable basis for measuring the carbon storage benefits of carbon offset projects.

Monitoring and verifying carbon storage can be expensive, depending on the level of scientific validity needed. This guide describes a system of cost-effective methods for monitoring and verification on a commercial basis, for three types of land use: forest plantations, managed natural forests and agroforestry. Winrock International's Forest Carbon Monitoring Program developed this system with its partners as a way to provide reliable results using accepted principles and practices of forest inventory, soil science and ecological surveys. Perhaps most important, the system brings field research methods to bear on commercial-scale inventories, at levels of precision specified by funding agencies.

Winrock's system assesses changes in four main carbon pools: above-ground biomass, below-ground biomass, soils and standing litter crop. It aims to assess the net change in each pool for project and non-project (or pre-project) areas over a specified time period.

Carbon monitoring efforts require specialized equipment, methods and trained personnel that can be expensive for individual organizations to procure and maintain. This is particularly true since most monitoring activities are likely to be performed infrequently — once every two to five years. In developing its monitoring system, Winrock has recognized these costs and aimed to minimize them. The system is therefore designed for collaboration between an organization with specially-trained personnel and local organizations at each project site.

The system involves the following components:

- baseline determination of pre-project carbon pools in biomass, soils and standing litter crop
- establishment of permanent sample plots for periodic measurement of changes in carbon pools
- plotless vegetation survey methods (*quarter point* and *quadrat* sampling)1 to measure carbon stored in non-project areas or areas with sparse vegetation
- calculation of the net difference in carbon accumulated in project and non-project land uses

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1In woody savannah areas, the quarter point method helps in laying out measurement units by using the distance between a systematic sampling point and the nearest tree or shrub. Quadrat sampling involves the use of a portable sampling frame to delimit an area for measurement.

- use of SPOT satellite images as gauges of land-use changes, and as base maps for a microcomputer-based geographic information system
- software for calculating minimum sample size, assigning sample unit locations (either in a systematic grid or randomly), determining the minimum spacing for plots and optimizing site-specific monitoring plans
- computer modelling of changes in carbon storage for periods between field measurements
- a database of biomass partitioning (roots, wood and foliage) for selected species

A companion volume, entitled *Field Tests of Carbon Monitoring Methods in Forestry Projects*, will describe field experience with the methods contained in this guide.

1. Introduction

This guide describes methods and procedures for measuring the organic carbon stored by forestry and agroforestry land uses over time. Such a monitoring effort assesses the net difference in organic carbon stored in soil[2] and forest biomass for project and non-project (or pre-project) sites over a specified period of time. The difference in carbon stored is the amount of carbon sequestered, or 'fixed', by the project.

Carbon sequestration is thought to be a promising means for reducing atmospheric carbon dioxide, an important greenhouse gas. To offset carbon emissions, at least 15 utility companies and other organizations are involved in Joint Implementation (JI) land-use projects involving plantations, improved forest management and natural forest preservation.[3]

A major constraint to successful forestry-based carbon offset programs is the lack of reliable, accurate and cost-effective methods for monitoring carbon storage. If carbon becomes an internationally-traded commodity, as it appears likely, then monitoring the amount of carbon fixed by projects will become a critical component of any trading system. Current efforts at the site level represent two extremes: either they are based on preliminary assumptions, or they involve intensive research efforts that are too expensive for widespread use. The system described in this guide is intended to provide a cost-effective, precise and accurate accounting of carbon storage in projects. To the extent possible, the methods are standard approaches to mensuration and analysis of biomass and carbon.

Quantitative monitoring of carbon sequestration over time, and to a lesser extent verification of estimates, requires a series of carbon inventories. For practical reasons, these inventories should employ permanent sample plots, with periodic measurement of these sample plots in baseline and project cases.[4] Furthermore, the economic realities of the costs and benefits of a carbon inventory should be considered in the design stage, so that expectations of precision are in harmony with the resources available for the monitoring effort.

1.1 Defining objectives

To maximize the utility of information collected in an inventory and to reduce monitoring costs, forest managers should define the various objectives for an inventory early, in advance planning.

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[2] In general, these methods will be used to monitory only organic carbon. Inorganic carbon stored in carbonate materials is not likely to change with the vegetation changes anticipated in most forestry projects.

[3] Faeth, P., R. Livernash and C. Cort. 1993. *Evaluating the carbon sequestration benefits of sustainable forestry projects in developing countries*. Washington, DC: World Resources Institute.

[4] The baseline case is defined as on-site conditions without project activities. The project case includes on-site changes in soil and biomass carbon that occur due to project activities.

This guide assumes that the primary objective of carbon monitoring and verification is to produce sound estimates of carbon sequestered by projects, for use in the trade of carbon credits (even though a system for trading carbon credits has not yet been finalized). Precision is an important aspect of this objective. When an international carbon trading system is established, it will likely set precision standards for monitoring carbon in land-use systems. Until then, decisions on precision level must be made on a project basis as the monitoring objectives are defined, so that the inventory can be designed to supply the desired precision.

It is possible and often desirable for a carbon inventory to have several concurrent objectives. The technical rigor required for carbon monitoring can drive the collection of other data on forest management, and make the process of forest monitoring more cost effective. Additional objectives might be to track important wildlife populations, or measure biological diversity or timber species growth. The use of permanent sample plots also provides opportunities to study nutrient flows, production sustainability, and other trends.

1.2 Factors in inventory design

The use of permanent sample plots is generally regarded as a statistically superior means of evaluating changes in forest conditions.5 Permanent plots allow efficient assessment of changes in carbon fixation over time, provided that the plots represent the larger area for which the estimates are intended. This means that the sample plots must be subject to the same management as the rest of the project area. The use of permanent plots also allows the inventory to continue reliably over more than one rotation. Finally, permanent plots permit efficient verification at relatively low cost: a verifying organization can find and measure permanent plots at random to verify, in quantitative terms, the design and implementation of a project's carbon monitoring plan. To achieve the same level of verification with temporary sample plots or other inventory approaches would require substantially more time and expense.

The decision on which carbon pools to measure is critical to inventory design. In general, all pools that are large and subject to substantial change over the project life should be measured. Those that are small or very slow to change may not need to be measured. It is likely that an international carbon trading regime will require the project monitoring of all pools that are likely to decrease over time.

For pools that are likely to increase, a key factor in the design of an inventory is the cost of measurement and analysis of each component relative to the economic value of fixed carbon. For example, if carbon credits are worth US$2 per ton, it does not make economic sense to spend $2.50 per ton on measurements that include root biomass. However, it probably does make sense to spend $1.00 per ton on measurements that quantify roots.

In the current pilot phase of Joint Implementation (JI), it is assumed that carbon will have economic value in the future.6 In terms of costs, most carbon sequestration projects have

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5 For more details on this, see Forest Measurements, 3rd edition, eds. T.E. Avery and H.E. Burkhart (New York: McGraw-Hill, 1983) or Forest Mensuration, 3rd edition, eds. B. Husch, C.I. Miller and T.W. Beers (New York: John Wiley and Sons, 1982).

6 Joint Implementation refers to cooperative development projects that seek to reduce or sequester greenhouse gas emissions as described in the U.N. Framework Convention on Climate Change.

already calculated the cost of carbon fixed on a per ton basis. Inventories that follow the system described in this guide should be designed based on calculations of the cost per ton of carbon, as specified by the project implementor. Figure 1 outlines the overall process for inventory design and implementation.

1.3 Effects of product end use

The long-term effectiveness of carbon sequestration depends in part on the end-uses of the wood produced through project activities. The more durable the wood product, the greater the project's carbon storage effect in the medium and long term. However, carbon stored in wood is obviously not stored permanently; organic compounds eventually decay and some will ultimately reappear as greenhouse gases. The impacts of carbon sinks are directly proportional to the "ton-years" of storage (that is, tons of carbon multiplied by the number of years for which the carbon is stored). *The methods described in this guide do not cover the storage of carbon in post-harvest sinks.* Anticipated disposition of biomass can be recorded in Form G.

Questions of "leakage"[7] and off-site baseline changes are also important to the overall Joint Implementation process. Off-site leakage may determine the success or failure of forest preservation projects, but it is extremely difficult to quantify. Such off-site impacts are perhaps best estimated using the Land Use and Carbon Sequestration (LUCS) model available from the World Resources Institute.[8]

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[7] In this context, leakage is the loss of carbon (primarily woody biomass) in non-project areas due to project activities. For example, leakage occurs if a natural forest area that was previously used locally for timber and firewood, is closed due to a preservation project, causing fuelwood and timber to be harvested elsewhere.

[8] For information on LUCS, contact the World Resources Institute, 1709 New York Ave., NW, Washington, DC 20006, USA.

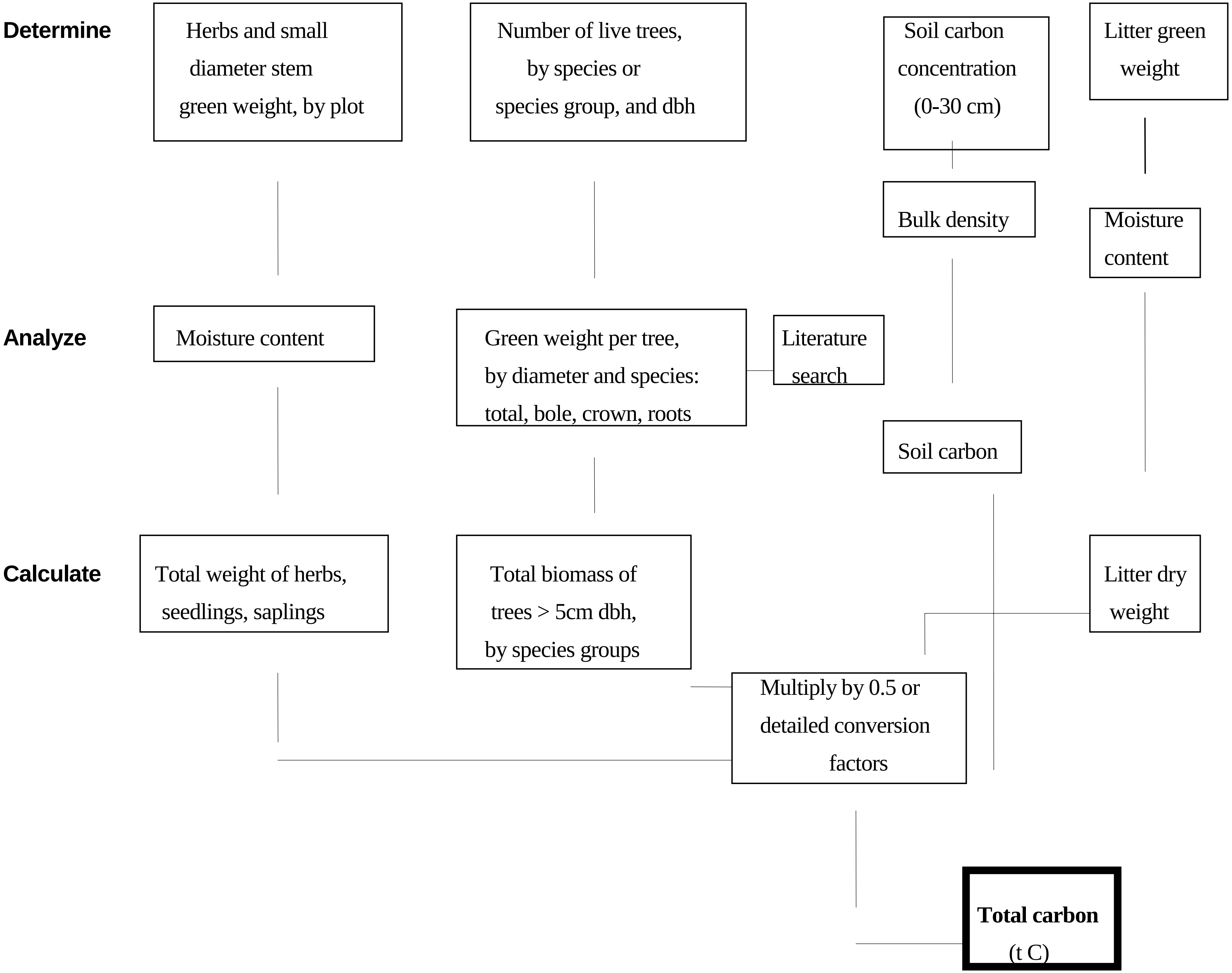

Figure 1. Flowchart for monitoring changes in major carbon pools in forestry and agroforestry projects.

Table 1. Examples of three levels of effort for carbon inventory

Level of effort	General description
Basic	This provides a very general, low-cost estimate of carbon stored in plantations. Less intensive sampling keeps costs low, but provides estimates of mean carbon fixation with accuracy approaching 30% of the estimated mean. Permanent sample plots are measured only twice: at plot establishment and at final harvest. Modelling produces interim estimates of carbon fixation in vegetation and soils.
Moderate	This level provides carbon storage estimates that are generally within 20% of the mean. Sampling intensity is greater, resulting in substantially more precise estimates than the basic inventory. Permanent plots are monitored every 2-3 years and at final harvest. Predictive models can be used to provide estimates of annual carbon fixation but would not be used in most applications.
High	This option produces estimates that are accurate within 10-15% of the amount of carbon sequestered, due to increased sampling and reduced reliance on models. Permanent sample plots are measured on an annual basis.

1.4 Inventory outputs

Carbon inventories of land-use projects can provide two general types of information: 1) carbon inventory reports that document changes in the quantities of carbon fixed due to project activities, and 2) commercial timber inventories that document quantities of merchantable timber. This guide describes only the first type, i.e., reports that indicate changes in carbon that result from project activities. Inventories of commercial timber, requiring slightly different data collection methods and analysis, can be done at relatively little additional cost.9

The inventory process usually yields two general types of outputs: baseline reports that describe carbon pool sizes at the beginning of the project and periodic reports that describe changes in these pools based on repeated measurement. The initial baseline carbon report provides an estimate of the quantity and distribution of carbon in vegetation and soils. This baseline would be produced before project activities begin and would serve as the benchmark from which future changes in carbon pool size would be calculated. The baseline report would be produced only once per site.

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9 For timber inventory methods compatible with those described in this guide, see Forest Measurements, 3rd edition, eds. T.E. Avery and H.E. Burkhart (New York: McGraw-Hill, 1983) or Forest Mensuration, 3rd edition, eds. B. Husch, C.I. Miller and T.W. Beers (New York: John Wiley and Sons, 1982).

Periodic inventory reports based on recurring measurement of permanent sample plots provide the basis for determining changes in carbon pools. These reports will describe measured quantities and distribution of organic carbon pools in soils and vegetation in project and non-project lands and calculate the net carbon stored by project activities and will verify project area and changes in biomass and soil carbon.10 In order to measure carbon change due to project activities, both the project and non-project cases must be monitored over time.

The methods in this guide have been field-tested under various conditions in Belize (Orange Walk District), Brazil (Minas Gerais and Para), Guatemala (La Union), the Philippines (Isabela Province), and the United States (Washington and Oregon). The experiences of these field tests are recorded in a companion volume entitled *Field Tests of Methods for Monitoring Carbon in Forestry Projects.*

2. Measuring Carbon Pools

Carbon inventories are in effect "snapshots" of carbon stored at the time of the inventory. To ensure these snapshots can be usefully compared with each other, it is important for the inventory team to be consistent in its use of measurement techniques and methods between different sites, stands, and inventory periods.

The following four carbon pools can be inventoried using the methods outlined in this guide:

1. Above-ground biomass/necromass
2. Below-ground biomass (tree roots)
3. Soil carbon
4. Standing litter crop

Appendices 4 - 6 describe the methods for measuring each of these carbon pools.

As mentioned earlier, permanent sample plots have two main advantages for carbon monitoring: (1) they provide more reliable data on trends in vegetation development than temporary plots do; and (2) they are more easily verified than other methods, since permanent plots can be revisited and remeasured by an external verifier.

The remainder of this guide refers to methods and procedures to be used with permanent sample plots that will be periodically monitored.

2.1 Inventory design

For the carbon inventories described in this guide, the sample unit is the permanent sample plot. The sample frame (i.e., the listing of all the sample units) is the project's land area, excluding buffer zones and areas that are not carbon sinks for project purposes.

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10 While the largest largest proportion of carbon changes usually occur in biomass, soil carbon is also likely to change due to cultivation and conversion to new species. For a more detailed description of the effects of land-use changes on soil carbon in the tropics, see *Dynamics of soil organic matter in tropical ecosystems*, eds. D.C. Coleman, J.M. Oades and G. Uehara (Honolulu: University of Hawaii Press, 1989).

Sampling design

There are four options for sampling design: complete enumeration, simple random sampling, systematic sampling and stratified random sampling. For carbon inventory, stratified random sampling generally yields more precise estimates for a fixed cost than the other options. Stratified random sampling requires stratification, or dividing the populations into non-overlapping subpopulations. Each stratum (or subpopulation) can be defined by vegetation type, soil type, or topography. For carbon inventory, strata may be most logically defined by estimated total carbon pool weight. Since that largely depends on above-ground biomass, stratification criteria that reflect biomass are generally most appropriate.

Useful tools for defining strata include satellite images, aerial photographs, and maps of vegetation, soils or topography. These should be combined with ground measurements for verifying remotely-sensed images (or *ground truthing*). The key to useful stratification is to ensure that measurements are more alike within each stratum than in the sample frame as a whole. A geographic information system (GIS) can automatically determine stratum size and the size of exclusions or buffer zones (e.g., village sites, non-project areas within the larger project area, stream buffers, archeological sites). Areas can also be determined manually using a planimeter or dot grid.

Sample size

The level of precision[11] required for a carbon inventory has a direct effect on inventory costs and, as noted earlier, needs to be carefully chosen by those who will use the inventory report. Once the level of precision has been decided upon, sample sizes must be determined for each stratum in the project area and for each carbon pool to be measured. Carbon inventory is more complicated than traditional forest inventory in that each carbon pool may have a different variance (amount of variation around the mean). So, while the standard error of the mean for above-ground biomass may be 20% of the mean, if the same sample sizes are used for each carbon pool the standard error for soil carbon may be 40%, and that for root biomass may be 80% or more. To simplify sampling design and the understanding of the precision presented in an inventory, sample sizes for each carbon pool should be determined separately. After that, the inventory manager can decide how many samples to collect for each pool.

Appendix 2 describes a spreadsheet for inventory decisions that will calculate sample size using standard formulae based on measured variation for the carbon pool to be sampled. The appendix describes two alternatives for determining sample size and allocating sample plots among strata: 1) sample plot allocation based on fixed precision levels and, 2) optimum allocation of plots among strata given fixed inventory costs.

Permanent plots cannot always be relocated (or reoccupied) for a variety of reasons (e.g., plot markers are overgrown or are removed by people, plots are burned or records are lost). To help ensure a minimum number of plots are available for remeasurement, it is prudent to increase the number of plots above the minimum in the initial sampling design. Increasing the minimum number of plots for the baseline by 10-20% provides a “cushion” that helps to

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[11] *Precision* is the degree of agreement in a series of measurements. *Accuracy* is the closeness of a measurement to a true value.

ensure that the minimum precision requirements will be met even if there are missing plots in subsequent inventories.

If biomass or soil carbon data are not available for a site, preliminary samples should be taken from 10 plots of equal area, perhaps as a training exercise for technicians. These data should be used to estimate the variance for calculating sample size.

Selection of sample units

The sample units will almost always be fixed-area permanent plots. Permanent plot locations can be selected either randomly or systematically. If stratified random sampling is used, sample units for each stratum can still be selected systematically. If little is known about the population being sampled, random selection of sample units is generally safer than systematic selection. If plot values are distributed irregularly in a random pattern, then both approaches are about equally precise. If some parts of the strata have higher carbon content than others, systematic selection will usually result in greater precision than random selection.

Map preparation

Once the sampling design, sampling sizes, and method for selecting sample units have been determined, the locations of the permanent sample plots must be marked on a map and/or the satellite image. Accurate, well-annotated maps are essential for finding permanent sample plots in the field. Using a GIS or desktop mapping system such as MapInfo can help automate this process and reduce the possibility for error. In the topographic map in Figure 2, 25 permanent sample plot locations in the eastern half of the map were determined using a systematic grid; sample units in the western half were selected randomly. Utilities for plot location allow precise descriptions of plot center locations and help crews to readily find any given plot with the use of a DGPS receiver.

A major advantage of mapping or GIS software is the ability to produce maps at many different scales quickly, and therefore customize the scale for each set of users. For example, funding agencies may be interested in small-scale maps (e.g., 1:50,000) that provide an overview of the project site. Project managers, on the other hand, may find larger-scale maps (1:25,000) more useful for viewing details of the project site that help them plan and manage all project components together. Field crews will generally want the largest-scale maps (1:10,000) to help them navigate. With a well-designed system for collecting and entering data, mapping software can automate most of this process.

A software package such as MapInfo, together with digital SPOT satellite images, can help an inventory manager to establish a systematic grid of sample plots at regular spacings and produce a list of coordinates for each plot. If desired, the program can list distances and compass bearings for navigating from plot to plot**.** However, these would normally be included in a route entered into the GPS receiver before the field crew begins each day’s trip to find and measure plots.

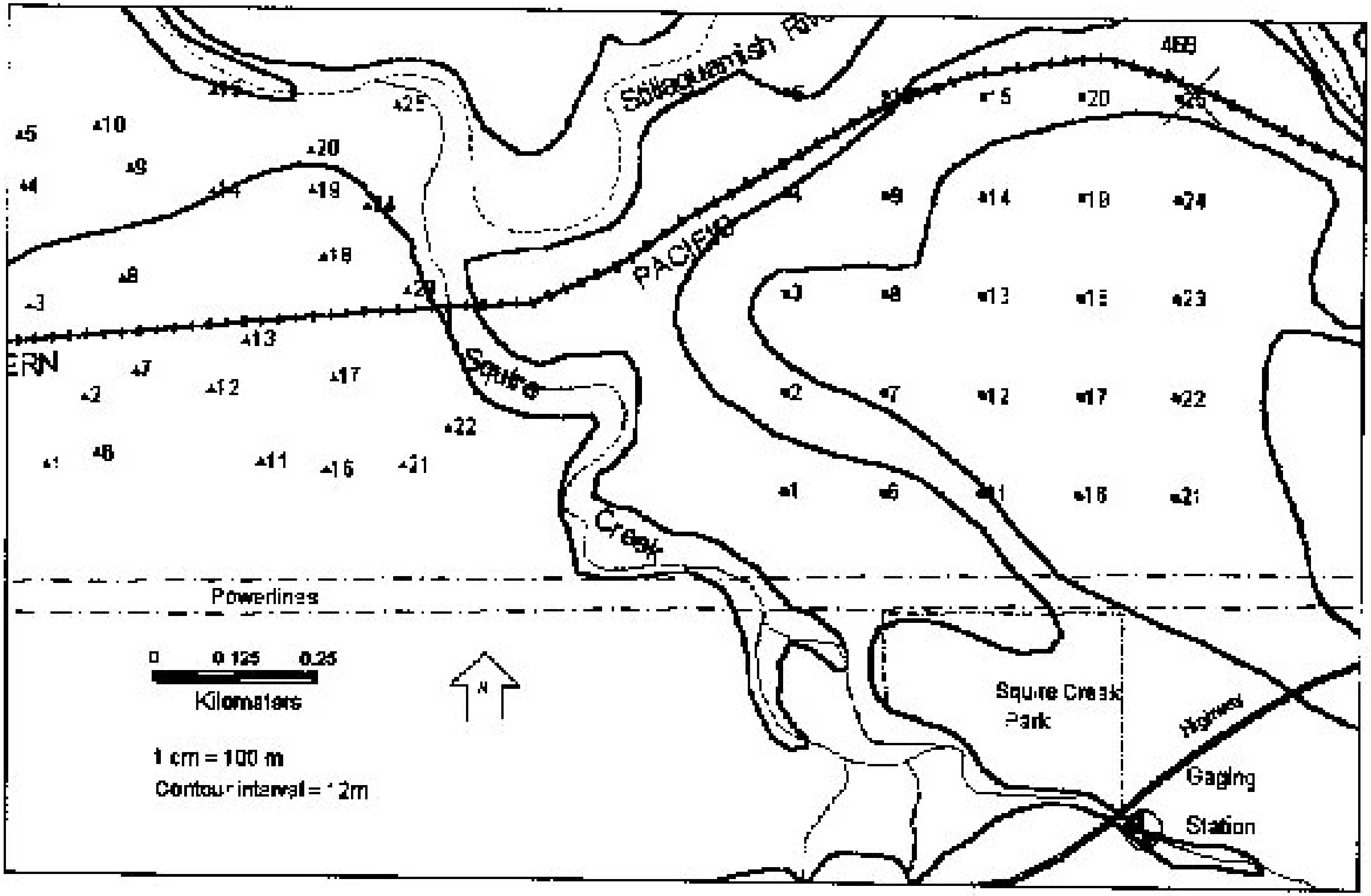

Figure 2. Example of random and systematic plot center arrangements

2.2 Inventory timing

Carbon inventories are likely to be infrequent. Unless they involve continuous monitoring (and substantially greater expense), inventories cannot account for seasonal fluctuations in the size of carbon pools. Because inventories measure carbon at just one point in the seasonal cycle, it is crucial to consider the seasonal timing of the inventory carefully before any other planning. In most cases, the inventory should take place during the season when field crews can work most efficiently and safely. This will usually be the part of the dry season with the most favorable temperatures for strenuous field work. For smaller projects or those that require fewer sample plots, selection of the season for inventory fieldwork can be more flexible, since they will require less time in the field than larger projects.

To eliminate seasonality as a source of variation in inventory results, subsequent inventories must be scheduled for the same season as the first inventory, preferably in the same month.

2.3 Measurement procedures

Permanent sample plots should be remeasured at an interval determined jointly by the inventory sponsor and manager, based on the desired level of precision. The only exception to the use of permanent sample plots might be the case of a low-intensity inventory employing a single assessment of biomass at the end of the tree-crop rotation. In this case, a conventional inventory using either fixed plots, strips or 3P sampling[12] can be used in place of permanent inventory plots.

If managers periodically inventory biomass (or wood volume) for commercial purposes, a second alternative to measuring permanent plots may be available. In this case, data collection for non-timber carbon (e.g., litter, soil carbon, understory vegetation) could be added to the timber inventory procedures during cruises in the project area.

Locating plots in the field

Two options exist for establishing and marking plot locations on the map and in the field:

Preferred option: Global Positioning System (GPS)

The use of GPS receivers to mark plot locations enables efficient and accurate placement and reoccupation of plots, particularly in projects with few roads. For natural forest projects or projects in dense vegetation, sample plot locations should be established using differential correction (to correct for systematic errors that result from the Defense Department's practice of "selective availability").[13] Differential correction ensures that plot centers are located as accurately as possible. Initial plot location can be done using post-processing differential correction with receivers capable of accuracy within 5 m. For crews to revisit plots in dense vegetation, the project will require real-time differential correction capacity (i.e., either carrier phase DGPS to correct signals transmitted over radio waves, the use of differential beacons, a satellite correction system such as Omnistar or the use of radio-modems for both base station and field crews).

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[12] *3P sampling* is sampling with probability proportional to prediction.

[13] A recent decision by the U.S. Government to remove selective availability will at some future time obviate the need for differential correction for many forestry applications.

Alternative: Compass bearing and distance

Relative bearings can be taken from known landmarks for approach lines, distances and reference points for each plot. GPS coordinates can also be used as the basis for compass bearing and distance. This is particularly useful when steep topography or very dense canopy cover at the plot site prevent reliable GPS readings. This information should be recorded on the CIDF (Appendix 1, Form E).

Above-ground biomass in project plots

Measure above-ground project biomass using a timber cruise of permanent inventory plots and biomass tables (Appendix 4). Measure the diameter of all woody vegetation of a minimum diameter and greater (e.g., > 2 cm) in dbh (diameter at breast height, 1.3 m). Paint a mark on each stem at dbh to ensure correct measurement for the next inventory. Take subsamples of smaller diameter woody vegetation and herbaceous plants using small quadrats or circular plots. Convert individual dbh values for each plot to biomass using single-entry biomass tables. Where single-entry tables do not provide adequate estimates of biomass, use double-entry tables based on dbh and height (i.e., length). Appendix 6 describes how to estimate below-ground biomass.

For tree species for which biomass tables do not exist, the project may need to develop the biomass tables. It is generally preferable to use biomass tables directly rather than to use wood-density values to convert stem wood volume tables to biomass, because wood density varies significantly among trees within a species. Biomass tables can be constructed using a minimum of 30 well-selected trees or with a “mean tree” approach (Appendix 4). Appendix 5 describes methods for herbaceous vegetation.

A last alternative to developing biomass tables is to use the general biomass equations found in Appendix 4. However, this alternative is not generally recommended due to the high variability between species.

Above-ground vegetation on non-project sites

Quantifying changes in non-project (reference case) vegetation is, in most cases, essential for quantifying a project’s net carbon accumulation. Non-project vegetation will most likely change during the project period, so the only way to quantify project benefits reliably is to monitor vegetation on both project and non-project sites and calculate the difference in carbon stored.

Most non-project (reference case) areas will not be in heavy forest cover and may not require permanent sample plots. For example, in savannahs that are regularly burned or agricultural lands subject to tillage, plotless sampling methods can yield acceptable levels of precision at lower cost. The plotless quarter point method is described in Appendix 4.

Below-ground biomass

Even at moderate levels of precision, measuring root biomass is time consuming and expensive due to the wide variability in the way that roots are distributed in the soil. For many projects, it might be best to estimate root biomass using a conservative ratio for shoot:root biomass as the basis for claiming carbon credit. For example, the lowest shoot:root ratio ever reported for Species X is 5:1. To develop a conservative estimate without measuring roots, an inventory could calculate root biomass as not less than 10 or 15% of above-ground biomass.

However, for cases in which more accurate estimates of below-ground biomass are economically feasible, Appendix 6 describes measurements using pit, auger/core sample and pinboard monolith methods.

Soils

Soils are often large storage pools for carbon, both organic and inorganic. Soil carbon can be determined effectively using composite samples that represent multiple plots. This helps to reduce costs of data collection and analysis, yet provides a reasonable estimate of soil properties.14 The sample size calculator described in Appendix 2 can also be used to calculate the number of samples required per composite soil sample. Appendix 5 describes methods for sampling and measuring soil carbon.

Measurement standards and check cruising

Measurement standards define the maximum allowable error in measurements. Table 2 provides suggested allowable limits of error. Measurements with error that exceed these standards should be rejected as unacceptable.

Table 2. Suggested allowable limits for measurement error

Measurement	**Allowable error**
Tie lines	
Bearing	±2° of the true bearing
Distance	±2° of the true horizontal distance
Permanent plots	
Missed or extra trees	No error within the plot
Tree species or groups	No error
Breast height	± 5 cm of the true height (1.3 m)
D.B.H.	± 0.1 cm or 1% whichever is greater
Circular plot radius	±1% of horizontal

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14 Peterson, R.G. and L.D. Calvin. 1982. Sampling. In *Methods of soil analysis, part 1*. Agronomy Monograph no. 9 (2nd Edition). ASA-SSSA, Madison, Wisconsin.

The following general standards are required for carbon inventories using permanent sample plots:

1. Describe sample locations accurately enough to enable a crew to revisit the sample plots.

2. Keep adequate records of all data.

3. Specify standards for stratification and sampling design for every inventory, and adhere to these standards carefully.

4. Take all measurements carefully, using properly adjusted instruments of proven accuracy. Make every effort to eliminate personal bias by using well-understood instructions and factual observation in the field.

5. Calculate sampling errors.

6. Inadequate marking, measurement or recording of data, or the sloppy location of plot centers, may indicate errors or biased location of sample plots. This may cause a sponsoring agency to reject the inventory.

Check cruising is the verification of field measurements, and involves remeasuring a percentage of plots to ensure reliable, accurate data of known quality. Check cruising is necessary for all cruise-based inventories. In general, check cruises should remeasure 1-5% of all plots within two weeks after initial measurement. The crew performing remeasurement should not include any members who participated in the initial measurements. Check cruising should be done with greater intensity (e.g., check cruising of 15% of the plots) for the first week's plots. Measurements for the second week might be monitored using a check cruise of 10%, and 5% for the third weeks' plots. This provides crews with direct feedback on their performance and helps to correct procedural errors before they become expensive to correct. As confidence increases in the crews' abilities to collect reliable data of known precision, the check cruise intensity might be reduced to random remeasurement of 1% of the plots.

3. Designing Monitoring Packages for Specific Land Uses

Project-specific monitoring must meet the specifications of the inventory sponsor and at the same time use methods and procedures that are appropriate for the site. Different forest types or land-uses may require different sets of the methods in this guide. Table 3 lists some of the comparisons and procedures required for the kinds of land-use likely to be included in Joint Implementation projects.

Packages of methods/procedures should be assembled to meet both the practical and technical requirements of a site (and the institution(s) conducting the monitoring and verification) and the cost of using these methods. Section 3.1 discusses general aspects of monitoring design by land use. Sections 3.2 and 3.3 describe some of the important economic issues relevant to monitoring designs for specific projects.

3.1 General requirements by land-use

Natural forest preservation

Natural forest preservation projects provide perhaps the greatest amount of fixed carbon in the early years of a JI project because biomass density is high and deforestation at non-project sites often releases large portions of stored carbon in biomass due to clearing, wood removals and burning. The primary carbon comparisons required for these types of projects are between the areas being preserved and the land-use(s) the forest would be converted to if the forest were not protected.

Satellite images are important tools in the monitoring of preservation areas because they provide a clear record of land-use change. Permanent plots can provide reliable trend data on carbon pool changes and are valuable in protected forest areas. If forest lands outside the protected area are being converted to agricultural fields, the only measurements required in the reference case will be soil carbon. If the reference case lands contain woody biomass or grasslands, then either permanent plots or transect methods are suggested for the measurement of biomass carbon.

Natural forest management

Monitoring the changes in carbon due to management of natural forests requires paired comparisons between forests managed with “improved” regimes and comparable areas using reference case management. The differences in stored carbon are likely to be smaller in natural forest management projects than in forest preservation or plantations. This may mean that for larger sample sizes will be required in forest management projects to attain the same level of precision as forest preservation or plantation projects.

Table 3. Procedures required for reference vs. project case comparisons

Land use	Comparison	Procedures required
Natural forest preservation	**Reference case:** Adjacent land converted from natural forest to agriculture or other uses	Temporary plots for soils, transect methods for perennial crops
	Project case: Preserved natural forest	Periodic satellite photos of project area, permanent sample plot measurements
Natural forest management	**Reference case:** Existing management practices	Periodic satellite photos of project area, paired permanent sample plot measurements.
	Project case: Introduced management practices	
Plantations	**Reference case:** Pre-project vegetation	Transect methods for above-ground woody biomass with sampling quadrats for herbs, soils and litter
	Project case: Plantations	Periodic satellite photos of project area, permanent sample plot measurements
Agroforestry/farm forestry	**Reference case:** Existing land use systems	Transect methods and temporary plots for above-ground woody biomass with sampling quadrats for herbs, soils and litter. Inter-
	Project case: Improved/expanded agroforestry or farm forestry areas	active survey methods are used to solicit farmer input and to provide information to farmers about project monitoring.

Layout of the paired plots is also critical to successful monitoring of improved forest management. Each plot in a pair should be in the same vegetation type with no readily discernible difference in site quality, stand morphology or population density. Plots should be located as close to one another as possible, provided adequate buffer or border space. A rule of thumb for determining border space is two times the height of dominant trees in the stand. Carbon should be calculated as the sum of the net carbon differences between each pair.

Forest plantations

Plantations are often the easiest projects to monitor because when compared to natural forests they usually have higher road densities, better records and easier access to plots. Permanent plot methods are appropriate in forest plantations, although the easy access and greater management intensity introduce a potentially high risk that the plots will be managed differently from surrounding project areas. To minimize that risk, plots should be marked inconspicuously using markers that are far from the actual plot centers coupled with a buried iron pipe or special marking magnets and a specialized metal detector. Plot locations should be kept confidential to avoid the intentional application of additional inputs to the plots.

Satellite imagery provides a clear picture of plantation size and location. When analyzed with mapping software it also provides a ready means of calculating strata and total project areas.

Agroforestry and farm forestry

Spatial variability and farm to farm differences in management are the greatest challenges for monitoring agroforestry or farm forestry areas. Most projects of this type will include farms that are widely dispersed and managed in different ways. Many of the methods used to measure carbon sequestration in natural forests can be directly applied to agroforestry plantings, but there are some important differences. These include:

- agroforestry plantings require intensive labor inputs, and are typically small in size.
- agroforestry plantings are often widely scattered over the landscape. Broad expanses of non-project vegetation may separate individual plantings.
- trees in agroforestry plantations are often widely spaced to provide light for associated crops. As a result, the tree canopy is discontinuous and may be highly variable.
- in some agroforestry systems, trees are arranged in regularly spaced rows. This could introduce bias into systematic sampling schemes arranged in linear grid-like patterns.
- Agroforestry plantings are usually established and maintained by small landholders. Thus, any measurement of an agroforestry plantation necessarily involves professional interaction with farmers that may not occur in other types of land-use projects.

3.2 Setting economic limits

Some potential JI projects do not fix enough carbon for a monitoring effort to be economically worthwhile. Although this should be evaluated prior to project approval, it may be necessary to make preliminary estimates of monitoring costs at the proposal development stage. When designing a monitoring system, the cost of measuring each component should be estimated and compared to the value of carbon. During the JI pilot phase there is no actual trading value for carbon, so the relative value of each measurement should be calculated and packaged in a way that fits the project budget.

The monitoring package design should depend on how much carbon will be fixed per unit area. For example, projects that fix less than 2 or 3 t C per hectare per year can not likely be monitored in a cost-effective way because the costs of measuring these quantities are nearly the same as the cost of monitoring 10 or 15 t C per hectare per year. When preparing a monitoring plan and budget, these economies of scale are important.

Project area is also an important factor in determining both the economic feasibility of monitoring and the cost per ton of carbon. In general, because fixed costs are a large part of the total monitoring cost, the larger the project area, the lower the unit costs for monitoring. It is likely that projects smaller than 1,000 ha will be very difficult to monitor in a cost-effective way with reasonable precision.

4. Tools

Because a carbon inventory might be estimating carbon worth millions of dollars, the tools for these inventories need to be accurate, rugged and durable to withstand the rigors of field use under adverse conditions. They should also contribute to efficient planning, data collection, analysis, and reporting. This section describes equipment for field work and software for modelling. Models can be useful tools for estimating changes in carbon pools for periods between inventories; but for traded commodities, models are not adequate substitutes for measurements.

4.1 Equipment

In order to perform an inventory accurately, reliably and at minimum cost, an inventory team must have good-quality equipment. Anything less can result in higher labor costs, greater safety risks and unreliable carbon estimates. The following list of field tools and equipment continues to evolve as methods are refined and new equipment becomes available. To some extent, equipment needs will vary with inventory objectives, available labor and skills, terrain, and vegetation or soil type. Figures 3 to 5 show examples of some of the equipment needed.

The following equipment and supplies are recommended for field crews:

Equipment

- compass/clinometer combination for navigation, plotting on the map, bearing and slope measurements
- diameter tape for measuring dbh
- loggers tape for measuring dbh and as a back-up for plot radius measurements
- Hagloff distance measure, tripod and extra threaded tripod adapter for measuring distance to trees for diameters, and for measuring fixed plot boundaries
- calculator for calculating height, diameter
- cruisers vest for carrying cruising equipment
- entrenching tool, folding shovel or soil corer for taking soil samples
- precision spring scales (e.g., Pesola 1kg + 300g) + weighing bags, e.g., Tyvek 10 x 17" bags (25.4 x 43.2 cm)
- sampling frames (2), round or square, hinged
- pruning saw and shears (e.g., Felco 60 and Felco 8)
- sheet holder
- two-way radio and extra batteries
- GPS (2) with differential correction capability and remote antenna mounted on fixed frame backpack (one as base station and one as remote), differential correction software, extra battery pack and charger
- notebook computer for database use and differential correction, and for generating maps

Supplies

- laminated maps or photos, with plot locations and coordinates
- pencils, marking pens, map scales
- ribbon (flagging) and painted high-grade PVC pipe for marking plot centers that are conspicuously marked
- plot cards, field aids and instructions
- rain gear
- safety equipment such as a first aid kit, hard hat, space blanket, waterproof matches, candle, insect repellent
- flashlight
- 50 cm x 50 cm piece of 5-mm mesh screen and small plastic tarp for screening and mixing soil samples
- sampling bags for soil, vegetation and litter, e.g., Tyvek 5 x 7" bags (12.7 x 17.8 cm)

Additional equipment for non-destructive biomass table measurements:

- Spiegel relaskop - metric scale for measuring tree diameters, heights and slope
- Jacob staff or monopod and ball joint adapter for use with relaskop
- bark gauge
- compact binoculars for use with relaskop

Additional equipment for verification measurements:

- hand-held data collection or pen-based computer

Additional requirements for real-time DGPS use in permanent plot reoccupation:

- radio modem transceivers (2)
- GPS base station capable of transmission

4.2 Models for interpolation

The size of carbon pools can be estimated for periods between inventories by using prediction models. Changes in soil and biomass carbon can be modeled using software packages such as Soil Changes Under Agroforestry (SCUAF), CENTURY and LUCS, using baseline survey data and estimates of biomass growth. SCUAF Version 2.0 is recommended for use with the methods described in this guide, mainly for the following reasons:

- Ease of use. SCUAF is menu-driven and relatively user-friendly.
- Relevance. SCUAF was designed for use in agroforestry and incorporates both soil and biomass predictions for carbon and nitrogen.
- Presence of a default data set (for basic-level monitoring). Data on a number of variables that are expensive to collect (e.g., root biomass, feedback factors, erosion rates) are provided in a default data set that has been carefully selected from the literature.

- Cost and availability. SCUAF costs less than US$50 and is readily available from the International Centre for Research in Agroforestry.[15]
- Documentation. The SCUAF manual is well written and provides good information on the software's theoretical basis and operations.

Appendix 3 describes the data collection requirements for SCUAF.

The prospect of saving on measuring costs by using computer models to predict future carbon storage may be tempting. However, the costs of accurate, verified modelling are likely to be at least as high as the costs of actual measurement, and perhaps greater. Modelling should only be used for interpolation, i.e., when investors require an estimate of carbon storage at a point in time between two actual measurements.

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[15] International Centre for Research in Agroforestry, United Nations Avenue, Gigiri, P.O. Box 30677, Nairobi, Kenya.

5.0 Reporting and Verification

The format and frequency of reports will depend in part on the inventory design, resources and the reporting requirements of the sponsoring agency. Use the reporting formats described in this section to present the results of carbon monitoring. Reports intended for use outside the project's technical staff should always include a summary explaining the consequences of the findings.

5.1 Reporting

The way in which a project reports carbon credits will likely be determined by governmental regulations or intergovernmental agreements. Until such guidelines are in place, the following two types of reporting might be considered.

1. Report mean values for carbon stored along with confidence limits (at p=0.05). The formula for confidence interval calcuations is:

$$CI = \overline{X} \pm ts_{\overline{X}}$$

where : t = a two-sided t value for a probability level of 0.05

$s_{\overline{X}}$ = the standard error of the mean from the carbon inventory

2. Report the Reliable Minimum Estimate (RME) as a conservative measure of the minimum quantity expected to be present with its probability.16 The formula for this calculation is:

$$RME = \overline{X} - ts_{\overline{X}}$$

where : t = a *one-sided* t value for a probability level of 0.05 (i.e., use p=0.10 in a two-tailed t table)

$s_{\overline{X}}$ = the standard error of the mean from the carbon inventory

For most current uses, reporting mean values with confidence intervals is probably most appropriate given the need for maximum incentives to potential investors in carbon offset projects.

5.2 Baseline

This report provides an estimate of organic carbon as it is distributed in vegetation and soils before start of the project. It is derived from data summarized in the Carbon Inventory Data Form (Appendix 1).

Project description

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16 For more details see Dawkins, H.C. 1957. Some results of stratified random sampling of tropical high forest. *Seventh British Commonwealth Forestry Conf.* Item 7 (iii).

Site name:
Contact person:
Project sponsor(s):
Project manager:
Local name of project site:
Address, State, Country:
Latitude:
Longitude:
Elevation (m):
Project species:

Accuracy level specifications

Baseline carbon distribution

Carbon pool	Area (ha)	Mean carbon density ($Mg\ ha^{-1}$)	Total carbon (Mg)	Confidence interval (Mg)
Reference case Above-ground Below-ground Forest floor Soil to depth of 30 cm Total - reference case	NA			
Project case Above-ground Below-ground Forest floor Soil to depth of 30 cm Total - project case	ha			
NET CARBON STORED THROUGH PROJECT ACTIVITY				

5.3 Reporting carbon changes

This format is for use in reporting changes in carbon stored due to project activities.

Dates:
Date of previous measurement:
Primary person responsible for monitoring:

Description

Site name:
Contact person:
Sponsors:
Project manager:
Local name of site:
Address, State, Country:
Latitude:
Longitude:
Elevation (m):
Primary species:

Accuracy level specifications

Site history since carbon statement or last inventory

Describe any significant changes in management, pest and disease problems, harvesting or other mortality.

Carbon distribution[17]

Carbon pool	Area (ha)	Mean carbon density (Mg ha^{-1})	Total carbon (Mg)	Confidence interval (Mg)
Reference case Above-ground Below-ground Forest floor Soil to depth of 30 cm Total - reference case	NA			
Project case Above-ground Below-ground Forest floor Soil to depth of 30 cm Total - project case	ha			
NET CARBON STORED THROUGH PROJECT ACTIVITY				

5.4 Verifying carbon monitoring estimates

Verification of carbon offset projects by a third party is similar to an accounting audit performed by an objective party. For greatest efficiency and the most useful results, the regular monitoring team and the auditing organization should agree on procedures and methods before start of the project.

A verification audit of carbon monitoring is a form of quality assurance that is presently required by the U.S. Initiative on Joint Implementation (USIJI). It is also likely to be required in future carbon offset land-use programs. Just as periodic audits are required for companies involved in other types of trade, a system of verification will be necessary in order to avoid needless litigation over project benefits and credits.

Agencies aiming to verify a forestry project's carbon storage estimates might follow the general procedures used by auditing firms in accounting. These include:

1. Prior agreement on carbon monitoring methods at the outset. If the verifying agency and the project's carbon monitoring team agree on a system of methods for measuring carbon before the project begins, then the process can be evaluated efficiently, with little danger of problems that would call monitoring estimates into question.

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[17] Carbon estimates are based on samples taken from permanent, fixed-area plots in sites prior to site preparation for establishment.

2. Review of all monitoring records, including field data collection sheets, spreadsheet/database files, computer model outputs, maps, remote-sensing data, plans, analyses, and reports.

3. Inspection and calibration of measurement and analytical tools used by the monitoring team.

4. Reoccupation and measurement of a random sample of the permanent plots used in the inventory.

5. If satellite imagery was not used to calculate project area for previous inventories, obtain and process images to verify project area.

Appendix 1: Carbon Inventory Data Form (CIDF)

Form A - Level of precision specifications

This form is designed to record instructions from the inventory sponsor regarding the desired levels of precision. (NOTE: Each carbon pool will likely have a unique variance and will require a unique sampling intensity to achieve a constant overall level of precision. For example, root biomass is likely to be more variable than above-ground biomass; foliage biomass is usually more variable than stemwood biomass.)

Form of decision from inventory sponsors:

____ General level of precision ____ Specific confidence limits (%)

____ Optimum precision for fixed-cost____ Cost based on precision

If a general level of precision is specified, record below the detailed specifications for modelling vs. field data collection, cost limits from sponsors, and overall desire for precision (e.g. basic, moderate, high):

Percentage of plots to be established in excess of the calculated minimum requirement:______%

Other specifications requested by inventory sponsor(s):

Form B - Project site description

A complete site description provides enough information to identify and locate the site and to allow some explanation of performance. Most data required for this form should be available from the project manager.

Site name:

Contact person:

Local name of site:

Address, State, Country:

Elevation range (m):

Ecological zone or general site type:

Most common slope class (flat or gentle = 0-5º; intermediate = 5-10o; steep = 11-45o; very steep >45o):

Mean annual rainfall (mm):

Rainfall regime (summer, winter, bimodal, uniform):

Maximum length of dry season (months <50mm):

Mean annual temperature (oC):

Surface soil texture (sand, loam, clay):

Sub-soil texture (sand, loam, clay):

Soil depth to impermeable layer (<25 cm, 25-50 cm, 50-100 cm, or >100 cm):

Surface soil pH (A horizon):

Sub-soil pH (B horizon):

Map with at least 3 latitude/longitude points[18]:

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[18] Points identified from: _____ local maps _____ known survey points
_____ differentially corrected GPS coordinates _____ uncorrected GPS coordinates

Form C - Sampling design

This form should be used in conjunction with the explanation for calculating sample size (Appendix 2).

Sampling design: Stratified systematic sampling with random start

Basis of stratification:

Source of variance estimates:

Variable used for estimate:

Number of samples used for estimate of sample plot requirements:

Acceptable error (% of treatment mean):

Stratum number[19]	Vegetation type	Area (ha)	Mean biomass (t ha-1)	Coefficient of variation (%)	Number of sample plots required[20]
TOTAL					

Append a map of the project area with sample plot locations marked and and coordinates for each permanent sample plot location.

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[19] Coding system: First letter = component (i.e., A or B), Second letter = Treatment (i.e., P = project case; R = reference case), Number = stratum number from vegetation map

[20] As calculated using the Winrock inventory sample size calculator

Form D - Satellite images

Satellite imagery, taken on an annual basis, can document the project area in an unbiased manner. Panchromatic SPOT imagery is recommended for this use due to the availability of high spatial resolution (10 m) in a 7.5’ or 15’ view. (However, this is a rapidly changing technology with new products and services constantly emerging.[21]) SPOT offers the additional advantages of (1) the ability to program the satellite cameras to cover a specific area at a specific time and (2) the convenience of images that do not require correction for topographic displacement in a commonly used map format.

Project managers, sponsors and field crews should receive copies of ortho-corrected, panchromatic prints. Digital image processing allows the input of geo-referenced images in a GIS such as MapInfo or ARC/Info.

Land area (including total area and mortality due to fire, clearing, insect and disease pests) should be determined annually from new satellite photos. In cases where cloud cover precludes the use of satellite photos, specify plans for either aerial photography or ground-based verification of the area. When ordering satellite images, the following parameters are generally needed:

Parameters or qualifiers	Value
Spectral mode	
Maximum acceptable cloud cover	
Scene date window	
Site location	
Angle range	

Imagery must be ordered at least two weeks before the start of the desired viewing window. Images take approximately four weeks to process after viewing.

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[21] If satellite images are desired for other uses, such as species identification or monitoring of stand health, options include the more expensive Landsat Thematic Mapper (30 m resolution reflected) and SPOT multispectral images (20 m resolution). For more information, see Monitoring vegetation change using satellite data, by B.N. Rock, D.L. Skole and B.J. Choudhury, in *Vegetation dynamics and global change*, eds. A.M. Solomon and H.H. Shugart (New York: Chapman and Hall, 1993).

Form E - Permanent plot locations

It is essential to mark clearly and record the locations of permanent sample plots to ensure efficient reoccupation of the plots for later measurements. Plot center markers painted with florescent paint and large quantities of bright colored flagging are recommended for marking plot centers. The following form can be used to record planned and actual plot locations.

When using a GPS receiver, the actual position will usually differ from the planned position due to the Defense Department's policy of selective availability (which introduces dithered satellite signals containing intentional errors) and/or difficult terrain at the planned location. In any case, it is important to record the actual position, using either the best average fix from the GPS receiver (if differential correction is not used) or the corrected position after the permanent plots are established and the corrections made.

Please note: this form must be accompanied by a map indicating permanent plot locations.

Plot Locations

Cruiser ________________ Date ___/___/___

Project ________________ Country________________

Plot location method (circle one): GPS Compass

Strata No.	Plot No.	Plot size	Landmark or known point	Bearing from landmark	Planned position		Actual position*		Elev. (m)	Comments
					Latitude	Longitude	Latitude	Longitude		

*If different from planned

Form F - Biomass measurements

Biomass accumulation should be monitored periodically by measuring vegetation at project and non-project sites. The plot card can be used to record measurements in permanent sample plots. The quarter-point data collection sheet can be used for data collected using plotless methods.

PLOT CARD

Carbon Inventory - Winrock International

Strata number___________ Plot number:_________ Waypoint number ______

Vegetation type:_______________ Crew chief ________________ Date __/__/___

Tree no.	Spp. Code	DBH (1.3m)	Tree no.	Spp. Code	DBH (1.3m)
1			21		
2			22		
3			23		
4			24		
5			25		
6			26		
7			27		
8			28		
9			29		
10			30		
11			31		
12			32		
13			33		
14			34		
15			35		
16			36		
17			37		
18			38		
19			39		
20			40		

Quadrat sampling		
Number of quadrats	Herb weight (g)	Litter weight (g)

Sub-samples for moisture content			
Herbs		Litter	
Sample no.	Weight (g)	Sample no.	Weight (g)
H		L	

Sub-samples		
Tree spp.	Sample no.	Soil
	W	Sample number
	W	S
	W	
	W	Sampling notes
	W	
	W	

Notes: Record the diameter of dead trees here, both standing and fallen.

Next waypoint number:_____ Bearing to next waypoint:______ Distance:______m

Landmarks?

Quarter Point Method Data Collection Form

Line number:							**Soil sample** **Number**	**Litter samples**		**Vegetation**	
Point number	Quarter number	Species or Species group code	DBH (1.3m)	Diameter @30cm	Height (m)	Distance (m)		Number	Sample weight	Number	Sample weight
	1										
	2										
	3										
	4										
	1										
	2										
	3										
	4										
	1										
	2										
	3										
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	3										
	4										
	1										
	2										
	3										
	4										
	1										
	2										
	3										

Form G - Anticipated disposition of biomass

To gauge the effectiveness of carbon sequestration projects, it is essential to have an idea of the intended fate or end-use of the biomass grown.

Check one or more option. If more than one, then indicate approximate percentage of disposition for each category.

____ Durable timber products (e.g., furniture, construction)

____ Pulp

____ Fuelwood (firewood or charcoal)

____ Foliage uses

____ Other (specify)

Non-project land use

____ Grazing

____ Periodic burning (specify approximate frequency)

____ Crops

____ Other (specify)

Form H - Laboratory methods

Soil and biomass carbon testing must be conducted by an established, reputable laboratory capable of periodic analyses throughout the project period. Total carbon is most often measured by either the dry combustion or wet combustion methods described by Nelson and Sommers.22 For soils that have carbonate minerals present, corrections need to be made for inorganic carbon using one of the methods described by Nelson and Sommers. Total nitrogen will be analyzed using the regular Kjeldahl distillation method, as described in Bremner and Mulvaney.23

Laboratory: ____

Address: ____
____
____

Telephone: _________________________ Fax number: _____________________________

Contact person for analysis: ____

Carbon analysis methods (check one):

____ dry combustion in a resistance furnace
____ dry combustion in a induction furnace
____ dry combustion using automated methods
____ wet combustion using a combustion train
____ wet combustion using a Van Slyke-Neil apparatus
____ other (specify)

Cost per sample _____

Total nitrogen analysis methods (check one):

____ regular Kjeldahl distillation method
____ modified Kjeldahl distillation method (describe)
____ other (specify)

Cost per sample _____

Notes:

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22 Nelson, D.W. and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. In *Methods of soil analysis, part 2*. Agronomy Monograph no. 9 (2nd Edition). Madison, Wisconsin: ASA-SSSA.

23 Bremner, J.M. and C.S. Mulvaney. 1982. Nitrogen - total. In *Methods of soil analysis, part 2*. Agronomy Monograph no. 9 (2nd Edition). Madison, Wisconsin: ASA-SSSA.

Form I - Inventory costs

The amount of time and money required to collect and analyze baseline and annual carbon data should be documented in this form. The most important use of this data will be for estimating the cost of sampling in each stratum to determine the optimum allocation of sample plots.

	Cost per Man-day	Total days	Cost
Planning			
Supervision			
Materials			
Transportation			
Other			
Training			
Instructors			
Materials			
Other			
Quarter point method survey			
Supervision			
Labor			
Transportation			
Other			
Permanent plot establishment			
Supervision			
Labor			
Transportation			
Other			
Permanent plot monitoring			
Supervision			
Labor			
Transportation			
Other			
Analysis, interpretation and reporting			
Personnel			
Laboratory analyses			
Materials			
Other			
Total inventory costs			

Appendix 2: Calculating Sample Size

The spreadsheet that follows includes sample data from non-project stands as an example of how the calculator can be used. Two approaches are used for determining sample size and sample plot allocations among strata: 1. optimum plot allocation based on fixed precision levels and, 2. optimum allocation of plots among strata given fixed inventory costs.24

1. Optimum plot allocation based on fixed precision levels

Use the following formula to calculate the number of sample units required to obtain a desired standard of precision:

$$n = \left(\frac{t}{A}\right)^2 \left(\sum_{h=1}^{L} W_h S_h \sqrt{C_h}\right)\left(\sum_{h=1}^{L} W_h S_h / \sqrt{C_h}\right)$$

where n = sample size (i.e., total number of sample plots required)

t = tabular value of Student's t

h = stratum number

L = the number of strata

$W_h = N_h/N$

N_h = number of sample units in stratum h

N = total number of sample units

S = stratum standard deviation

A = allowable error expressed in units of the mean

C_h = the cost of selecting a sample plot in stratum h

Allocation of these sample plots among strata is calculated as: $n_h = np_h$

where: n_h = number of sample plots for stratum h

n = total number of sample plots

and

$$P_h = \left(W_h S_h / \sqrt{C_h}\right) / \left(\sum_{h=1}^{L} W_h S_h / \sqrt{Ch}\right)$$

---

24 For a more detailed description of this approach see *Forestry handbook* (2nd edition), ed. K.F. Wenger (New York: John Wiley and Sons, 1984) and *Sampling techniques* (3rd edition), by W.G. Cochran (New York: John Wiley and Sons, 1977).

2. Optimum allocation of plots with fixed costs

If costs for sampling are fixed before sample size or plot allocations are determined, plot allocations can be assigned to minimize the inventory cost. The second portion of the spreadsheet performs these calculations using the following formula:

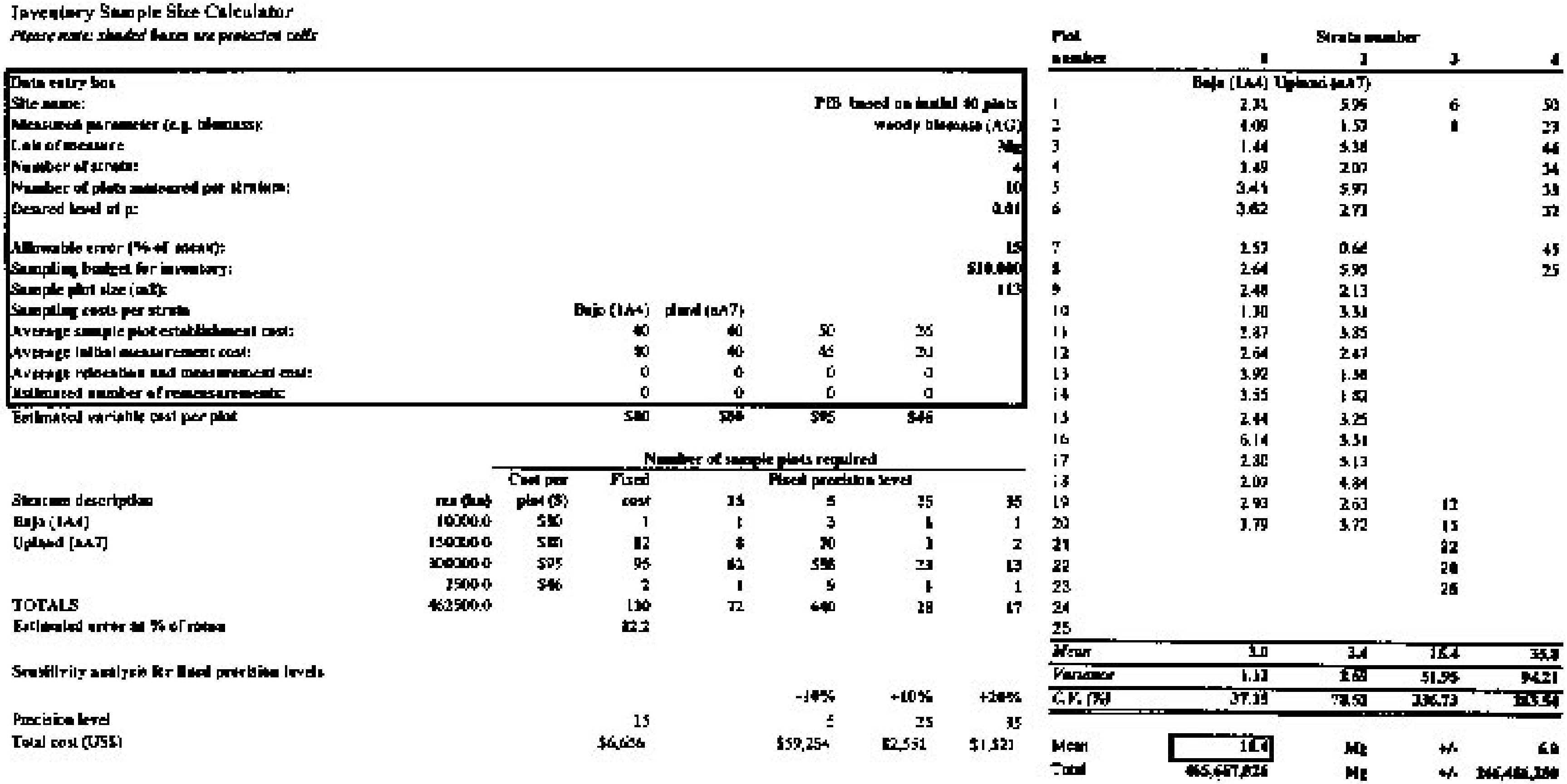
$$V_c = n \sum_{h=1}^{L} C_h P_h$$

where: V_C = variable costs for sampling

The user inputs include site name, measured parameter (e.g. woody biomass), number of preliminary sample plots used to calculate plot-to-plot variances, desired level of probability (p), allowable error (in % of the mean), sampling budget (if variable costs for sampling are set before sample size is calculated), sample plot size, costs for the establishment and measurement of sample plots, and the proposed number of times measurements will be made after plot establishment and baseline measurement. The minimum value for planned number of samplings is one (final measurement).

When using the formula**,** the following conventions must be used:

- If the mean and standard deviation values are not calculated from sample plot data in the spreadsheet, they must also be entered for each stratum.
- Cost values must be entered into the column labeled "Cost per plot" near the bottom of the sheet. Calculate cost per plot using the input values in the box at the top of the sheet, but enter these manually in the cost per plot cells to allow separate cost values for each stratum.



Inventory Sample Size Calculator

Please note: shaded boxes are protected cells

Data entry box				
Site name:	PEB based on initial 40 plots			
Measured parameter (e.g. biomass):	woody biomass (AG)			
Unit of measure	Mg			
Number of strata:	4			
Number of plots measured per stratum:	10			
Desired level of p:	0.01			
Allowable error (% of mean):	15			
Sampling budget for inventory:	$10,000			
Sample plot size (m2):	113			
Sampling costs per strata	Bajo (1A4)	pland (aA7)		
Average sample plot establishment cost:	40	40	50	26
Average initial measurement cost:	40	40	45	20
Average relocation and measurement cost:	0	0	0	0
Estimated number of remeasurements:	0	0	0	0
Estimated variable cost per plot	$80	$80	$95	$46

				Number of sample plots required			
		Cost per	Fixed	Fixed precision level			
Stratum description	rea (ha)	plot ($)	cost	15	5	25	35
Bajo (1A4)	10000.0	$80	1	1	3	1	1
Upland (aA7)	150000.0	$80	12	8	70	3	2
	300000.0	$95	96	62	558	23	13
	2500.0	$46	2	1	9	1	1
TOTALS	462500.0		110	72	640	28	17
Estimated error as % of mean			12.2				

Sensitivity analysis for fixed precision levels				
		-10%	+10%	+20%
Precision level	15	5	25	35
Total cost (US$)	$6,626	$59,254	$2,551	$1,521

Plot	Strata number			
number	1	2	3	4
	Bajo (1A4)	Upland (aA7)		
1	2.31	5.95	6	50
2	4.09	1.57	8	23
3	1.44	5.38		46
4	1.49	2.07		34
5	3.45	5.97		33
6	3.62	2.73		32
7	2.57	0.64		45
8	2.64	5.95		25
9	2.48	2.13		
10	1.30	3.31		
11	2.87	3.85		
12	2.64	2.47		
13	3.92	1.38		
14	3.55	1.82		
15	2.44	3.25		
16	6.14	3.51		
17	2.30	3.13		
18	2.07	4.84		
19	2.93	2.63	12	
20	3.79	3.72	15	
21			22	
22			20	
23			26	
24				
25				
Mean	3.0	3.4	16.4	35.9
Variance	1.13	2.88	51.95	94.21
C.V. (%)	37.19	78.50	336.73	153.54

Mean	10.0	Mg	+/-	6.0
Total	465,657,826	Mg	+/-	166,486,380

Appendix 3: Inputs for Carbon Modelling with SCUAF

The data required for carbon modelling using the Soil Changes Under Agroforestry (SCUAF) software are listed in the table below. Data on soil organic carbon, tree growth rates, biomass partitioning, and site descriptions must be entered before running models. All inputs, including defaults, must be listed in the form. If data other than the default values are used, the source of this data should be listed in the "Source" column.

The following are inputs required to use SCUAF:25

Input	**Value**	**Source**
1 CYCLE Cycle selected for modelling **If carbon cycle only is selected, it is not necessary to input data on nitrogen.**	1 Carbon Cycle 2 Carbon and Nitrogen Cycles	
2 DOCUMENTATION File name Title Source Location Date Notes		

25The source references indicate values that are different from the SCUAF default data set.

3 PHYSICAL ENVIRONMENT		
Climate:	1 Lowland humid 2 Lowland subhumid 3 Lowland semi-arid 4 Highland humid 5 Highland subhumid 6 Highland semi-arid	
Soil texture:	1 Medium textured 2 Sandy 3 Clayey	
Drainage:	1 Free 2 Imperfect 3 Poor	
Soil reaction:	1 Strongly acid 2 Acid 3 Neutral 4 Alkaline	
Slope class:	1 Flat 2 Gentle 3 Moderate 4 Steep	
4 AGROFORESTRY SYSTEM	Period 1 2 3 4 5 6	
Length (years) Fraction of land under trees Fraction of land under crop Is it a cut year? (Yes/No) What fraction of tree is N-fixing? What fraction of crop is N-fixing?		

5 INITIAL SOIL CONDITIONS **DEPTH** Topsoil depth (cm) Soil depth considered (cm) Total depth of soil (cm) **CARBON** Initial Carbon, Topsoil (percent) Initial Carbon, Subsoil (percent) Bulk density, Topsoil (g/cc) Bulk density, Subsoil (g/cc) Initial soil Carbon (kg/ha) **NITROGEN** Initial Nitrogen, Topsoil (percent) Initial soil Nitrogen (kg/ha)		
6 EROSION Soil Erosion (kg/ha/yr) = Climate Factor * Soil Erodibility Factor * Slope Factor * Cover Factor * 1000 Enter best estimate for each factor: Climate factor Soil erodibility factor Slope factor Cover factor under tree Cover factor under crop Soil erosion under tree (kg/ha/yr) Soil erosion under crop (kg/ha/yr) Tree proportionality factor Measured soil erosion in Year 1 (kg/ha/yr) Carbon enrichment factor Nitrogen enrichment factor		

7 INITIAL PLANT GROWTH		
Tree, Net Primary Production, above-ground (kg DM/ha/yr)		
Crop, Net Primary Production, above-ground (kg DM/ha/yr)		
Roots as a fraction of above-ground NPP, tree		
Roots as a fraction of above-ground NPP, crop		
NPP in parts of tree (kg/ha/yr):		
Leaf		
Fruit		
Wood		
Root		
NPP in parts of crop (kg/ha/yr):		
Leaf		
Fruit		
Wood		
Root		
Fractions of Tree retained as growth annually:		
Leaf		
Fruit		
Wood		
Root		
Fractions of Crop retained as growth annually:		
Leaf		
Fruit		
Wood		
Root		
Proportion of tree roots that are coarse roots		
Proportion of crop roots that are coarse roots		
Is any part of tree or crop retained as growth in cut year (Yes/No)		
If Yes:		
Fractions of Tree retained as growth during cut year:		
Leaf		
Fruit		
Wood		
Root		
Fractions of Crop retained as growth during cut year:		
Leaf		
Fruit		
Wood		
Root		
Fraction of roots growing below soil depth considered:		
Tree roots		
Crop roots		

CARBON Carbon Fraction in dry mass, Tree Carbon Fraction in dry mass, Crop **NITROGEN** Nitrogen % in: or Carbon:Nitrogen ratio of: Tree Leaf Tree Fruit Tree Wood Tree Root Crop Leaf Crop Fruit Crop Wood Tree Root or Crop Root		
8 ADDITIONS Organic (kg DM/ha/yr) Carbon fraction in organic additions Nitrogen percent in organic additions or Carbon:Nitrogen ratio in organic additions Fertilizer (kg/ha/yr) Nitrogen fraction in fertilizer	Period 1 2 3 4 5 6 Period 1 2 3 4 5 6	

9 REMOVALS		
A: HARVEST		
Fraction of Tree harvested annually:		
Leaf		
Fruit		
Wood		
Root		
Fraction of Crop harvested annually:		
Leaf		
Fruit		
Wood		
Root		
Additional fraction of Tree harvested in cut year:		
Leaf		
Fruit		
Wood		
Root		
Additional fraction of Crop harvested in cut year:		
Leaf		
Fruit		
Wood		
Root		
B: OTHER LOSSES FROM SYSTEM		
Are there any losses of plant material from the system other than harvest (e.g. burning)? (Yes/No) If Yes:		
Fraction of Tree lost annually:		
Leaf		
Fruit		
Wood		
Root		
Fraction of Crop lost annually:		
Leaf		
Fruit		
Wood		
Root		
Additional fraction of Tree lost in cut year:		
Leaf		
Fruit		
Wood		
Root		
Additional fraction of Crop lost in cut year:		
Leaf		
Fruit		
Wood		
Root		

10 SOIL PROCESSES		
CONVERSION LOSSES (Litter to Humus)		
Fraction of above-ground parts lost through oxidation		
Fraction of roots lost through oxidation		
Fraction of organic additions lost through oxidation		
Fraction of coarse tree roots decaying at least 1 year later		
Fraction of coarse crop roots decaying at least 1 year later		
Fraction of remaining coarse tree roots decaying 2 years later		
Fraction of remaining coarse crop roots decaying 2 years later		

HUMUS DECOMPOSITION CONSTANTS		
Number of humus fractions considered (1 or 2)		
LABILE HUMUS		
K for the tree		
K for the crop		
For 2-fraction humus only:		
STABLE HUMUS		
K for the tree		
K for the crop		
Fraction of humified litter becoming labile humus		
Fraction of labile humus transformed annually to stable		
NITROGEN CYCLE		
NITROGEN GAINS		
Symbiotic Fixation per unit area of N-fixing Tree (kg/ha/yr)		
Symbiotic Fixation per unit of N- fixing Crop (kg/ha/yr)		
Fraction of symbiotic fixed N entering soil humus		
Non-Symbiotic Fixation (kg/ha/yr)		
Throughfall and stemflow (kg/ha/yr)		
NITROGEN LOSSES		
A. Mineral N of organic origin:		
Fraction of mineral N leached under tree		
Fraction of mineral N leached under crop		
Fraction of mineral N lost		
- by gaseous losses (dentrification + volatilization)		
- by fixation onto clay minerals (net)		
B. Fertilizer N:		
Fraction of fertilizer N leached under tree		
Fraction of fertilizer N leached under crop		
Fraction of fertilizer N lost:		
- by gaseous losses (denitrification+volatilization)		
- by fixation onto clay minerations (ncl)		

11 SOIL/PLANT FEEDBACK FACTORS CARBON Rise or fall in soil carbon, relative to initial state, of 1 percent causes increase or decrease in rate of plant growth by x percent: For Tree For Crop NITROGEN Rise or fall in soil nitrogen, relative to initial state, of 1 percent causes increase or decrease in rate of plant growth by x percent: For Tree For Crop SOIL DEPTH Rise or fall in soil depth, relative to initial state, of 1 percent causes increase or decrease in rate of plant growth by x percent: For Tree For Crop		
NOTES		

Appendix 4: Measuring Woody Biomass

Woody biomass will nearly always be the largest and most easily manipulated carbon pool in carbon storage forestry projects. The inventory approaches for woody biomass are:

> 1. Measure the woody biomass of trees larger than a minimum diameter (e.g. >5 cm dbh) in project and non-project areas using timber cruises of permanent, continuous inventory sample plots. At the same time, sample the herbaceous biomass, standing litter crop and soil carbon vegetation, using the methods described in Appendix 5.
>
> 2. If permanent plots are not desirable or practical (due to frequent wildfire or grazing, for example), use the plotless quarter point vegetation survey to evaluate biomass and carbon content of vegetation on non-project sites. In plantation projects, the quarter-point method (which uses the distance between a systematic sampling point and the nearest tree or shrub) can be used to monitor lands left under natural vegetation. For preservation projects, this method can be used to monitor changes in lands converted to agriculture or other land uses with low tree population densities.

A. Timber cruising

Use permanent, inventory plots to measure timber on project and non-project sites, following a stratified random sampling design. In general, most carbon sequestered by project activities will occur in the largest diameter classes, so the timber cruise part of the inventory requires particular care.

Size and shape of fixed plots

Circular plots established using a well-identified plot center and a digital distance measure are recommended (Table 4). Optimal plot size can also be calculated using the following formula26:

$$Size = P_1 \frac{t^2}{m}$$

where: P_1= size of plot used in preliminary sample to assess time and variation in any unit of area; t = average travel time between neighboring plots in minutes; m=average plot measurement time for plot size P_1 in minutes

To calculate optimal plot size, measure a minimum of three plots of size P_1. Plots should be separated by the same distances anticipated in an actual inventory. Travel speed between plots and the plot measurement time (m) should be recorded. Calculate t by dividing the distance between neighboring plots by the travel speed or measure and average travel time between plots. Calculate P using the formula above.

---

26 Zeide, B. 1980. Plot size optimization. *Forest Science* 26:251-257.

Table 4. Plot radii for carbon inventory plots

Plot size (m^2)	Plot radius (m)	Area per tree (m^2 $tree^{-1}$)	Application
100	5.64	0 - 15	Very dense vegetation, stands with large number of small diameter stems, uniform distribution of larger stems
250	8.92	15 - 40	Moderately dense woody vegetation
500	12.62	40 - 70	Moderately sparse woody vegetation
666.7	14.56	70 - 100	Sparse woody vegetation
1,000 or use quarter point method	17.84	> 100	Very sparse woody vegetation

Relating diameter to biomass

Biomass tables or equations are needed to relate dbh and the number of plants per ha to total biomass. Biomass tables should therefore be sought for important species of native vegetation. Where these tables are not available, there are three alternatives:

1. Develop biomass tables for each important tree species using the method described in section C of this appendix. This is the most precise (and most costly) approach.

2. Develop biomass tables for groups of tree or shrub species. The most useful groupings may be by morphology class (e.g., single-stemmed trees, multiple-stemmed trees, shrubs).

3. Use one of the general biomass equations found in section C. This is the least precise approach, but also the least expensive. Given the wide range of species included in these equations, they should not be used except where the alternatives above are not possible.

B. Non-project woody vegetation

This method should be used to measure natural vegetation prior to project establishment at the same interval set for the measurement of the permanent inventory plots in the project. To save time in laying out plots in measuring woody savannah vegetation, use the quarter point method,27 which uses the distance between a systematic sampling point and the nearest tree or shrub.

The steps for this method are:

1. Establish a series of parallel sample lines 100 m apart. Locate sample points every 10 m along each line.

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27 For a more detailed description of this approach see Methods of sampling lesser vegetation, pp. 58-59 in *Forestry handbook* (2nd edition), ed. K.F. Wenger (New York: John Wiley and Sons, 1984).

2. At each sample point, divide the immediate area into quarters using the sample line plus a second line that crosses the sample point perpendicularly to the sample line. Figure 3 demonstrates placement of line and sample point, along with quarter numbers for each sample point.

3. Collect species and diameter data using the data collection form. For shrubs and small trees with low branching, measure diameter at 30 cm above the ground; for trees with better tree form, use dbh at 1.3 m. Also record the distance from each tree or shrub to the sample point. A minimum of 100 distance measurements are required per stratum.

4. Calculate average distances as follows:

   - Average the four distances at each point, then average the distances for the entire sample area. Use this number to calculate the mean area per tree as: $M = d^2$, where M = mean area per tree in m2 and d = average distance over the entire sample area.
   - For the total sample area, calculate density using the formula: D = 10,000 / M, where D = trees per hectare.[28]
   - Construct a stand table, with appropriate size diameter classes, and estimate biomass based on a biomass table.

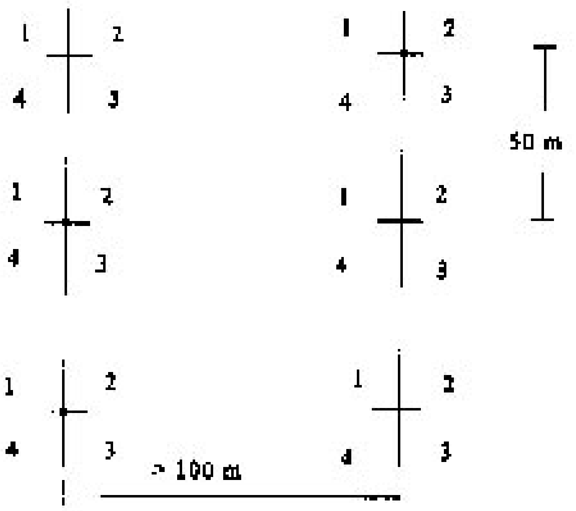

Figure 3 Sample point layout using quarter-point plotless method

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[28] If only a few species predominate, then accuracy is probably increased by determining biomass and carbon content by individual species. The method outlined in this section presumes relatively high species diversity and relatively low return to the additional investment needed to estimate non-project biomass by species.

C. Developing biomass tables[29]

Tree biomass weight tables show the average weight of individual trees for one or more dimensions, usually stem diameter alone (for local tables) or stem diameter along with height or length. The tables employ data obtained in destructive sampling. Through regression analysis, wood or foliage weight can be related to dbh, diameter at 0.3 m, and height. This appendix describes the process for developing standard biomass weight tables. Developing local weight tables is not recommended in view of their limited application and the great deal of effort they require, as well as the duplication of effort they involve.

Planning a weight table

Critical decisions must be made before beginning to develop a weight table, including:

- Defining the range of tree or shrub dimensions to be covered by the table.
- Defining the type(s) of biomass to be included in the table(s); this may include stem wood, stem and branch wood, or foliage; a table will need to be developed for each biomass type.
- Determining what measurements to use in relating biomass to a practical field measurement (e.g., d, dbh, or h).
- Defining size classes throughout the range of tree sizes.

Field sampling

A key issue is the number of trees necessary to develop a weight table for a given species. Estimates from many recent biomass studies suggest that 30-100 trees are enough for a regional table using stratified sampling of the population. Sufficient evidence supports the case that if sample trees are selected in equal or near-equal numbers for each size class, 30 trees for an individual tree biomass table are adequate. At least 30 well-selected trees should be used per species for individual tree biomass tables, unless the tables are to be used only for a specific site. For such purposes, as few as 12 trees may be adequate.

For calculating foliar nutrient content, more samples may be needed for foliage and branches than for stem wood. If scarce funds prevent the measurement of more than 30 sample trees for foliage, consider reducing the number of samples for stem wood in order to make resources available for foliage and branch sampling.

Partitioning and weighing

Each individual tree or shrub should be harvested; measured for diameter, length, and height[30]; and divided into the major components defined during the planning stage. Length measurements are recommended, but if vertical height is to be included as an independent variable, the measurement must be taken before the tree is harvested. Individual components (stem, branches, leaves, etc.) should be divided into several size classes for convenient handling and sub-sampling. Sub-samples should be taken to determine moisture content and specific gravity.

Techniques for weighing tree components depend largely on tree size and the availability of equipment. Take care to keep each tree and its parts separate from other trees. The best way to ensure

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[29] This section is taken largely from *Standard research methods for multipurpose trees and shrubs*, eds. K.G. MacDicken, G.V. Wolf and C.B. Briscoe (Arlington, Virginia: Winrock International, 1991).

[30] *Length* is the measured distance of a tree or specified portion of a tree following the lean or curvature, not necessarily vertical or straight; *height* is the vertical distance between a standing tree's apical bud and ground level.

this is to partition and weigh only one tree at a time. Measure green weight in the field. To calculate moisture content, sub-samples should be taken, dried at 80° C and re-weighed.

Although harvesting is the preferred way to develop weight tables, it is not always possible due to conservation or regeneration considerations. For biomass tables from non-destructive samples, calculate stemwood volumes and convert them to biomass using specific gravity for wood and expansion factors for canopy biomass. This requires a device for measuring diameter, such as a Wheeler pentaprism caliper, Spiegel Relaskop or laser measuring device. A sample form for recording data to construct biomass tables or volume tables using a metric Relaskop follows.

Analysis

Regression analysis should be performed for each biomass type defined during the planning process. To make the tables useful for the widest possible range of environments, at least one complete set of equations and weight tables should include both diameter and height terms.

The most common equations for biomass types include:

Biomass Type	Most Common Equation(s)*
Whole Tree	$B = b_0 + b_1D^2H$ $B = b_0 + b_1D$
Woody Biomass	$B = b_0 + b_1D^2H$
Branch, Foliage, or Crown Weight	$B = b_0 + b_1D^2$ $B = b_0 + b_1D$

**B* = predicted total or above-ground biomass, *D* = diameter (cm) at breast height (1.3 m), *H* = total height (m), $_0$ and $b1$ = regression parameters estimated from the data.

Results should be represented as both regression equation and table to allow the widest possible application of the work. When tables are unavailable and it is not practical to develop species-specific biomass tables, the following general equations can be used:

Climate type based on annual rainfall	Equation	R^2 adjusted
Dry (<1500 mm)	$y = 34.4703 - 8.0671\ D + 0.6589\ D^2$	.67
Moist (1500-4000 mm)	$y = 38.4908 - 11.7883\ D + 1.1926\ D^2$ $y = \exp[-3.1141 + 0.9719 \ln(D^2H)]$ $y = \exp[-2.4090 + 0.9522 \ln(D^2HS)]$ $H = \exp[1.0710 + 0.5677 \ln D)]$	.78 .97 .99 .61
Wet (>4000 mm)	$y = 13.2579 - 4.8945\ D$ $y = \exp[-3.3012 + 0.9439 \ln(D^2H)]$ $H = \exp[1.2017 + 0.5627 \ln D]$	.90 .90 .74

SOURCE: Brown, S., A.J.R. Gillespie and A.E. Lugo. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science* 35:881-902.

where: exp [...] means " raised to the power of [...]"
y = above-ground biomass in kg
H = height in m
D = diameter at breast height (1.3 m)
S = wood density in units of tons/m3

NOTE: These equations are valid only for stems with dbh >5 cm.

The mean tree technique for biomass estimation

Allometry is an effective method for accurately estimating biomass of trees, tree components and stands. However, the labor and expense of constructing and validating the necessary equations limit the application of the allometric approach in biomass sampling. Many of the allometric equations developed in the past were published in obscure journals, and furthermore have restricted applicability outside the area of their development.

The mean tree technique can be a cost-effective alternative to more time-consuming allometric methods. The mean tree technique was developed by several investigators during the 1960's and 70's (Baskerville 1963; Attiwill and Ovington 1968; Crow 1971; Madgwick 1970; Madgwick and Satoo 1975; Madgwick 1981; Satoo and Madgwick 1982). The concept behind the method is that an average-sized tree will also have an average amount of biomass. The usual approach is to select a tree or trees of mean basal area. Basal area tends to be a good predictor of total biomass, since diameter, basal area, and sapwood area all have a similar functional relationship to the quantity of live foliage and branches in the crown. The selected trees are then destructively sampled to determine their biomass. Subsampling may be used in the case of large trees (see Satoo and Madgwick 1982 for detailed applications of subsampling tree components). The mean tree weight is then multiplied by the number of trees in the stand to obtain an estimate for the total stand biomass. This basic technique can be modified by including stratified random sampling, the basal area ratio method, or by using weighted average values (Madgwick and Satoo 1975; Satoo and Madgwick 1982).

Properly used, the mean tree technique has several significant advantages: it is fast, it can be accurate, and it does not require elaborate computations. It is most appropriately applied in homogenous, even-aged, and well-spaced stands. The accuracy of this technique declines in diverse stands with a wide array of bole diameters and tree sizes. Most agroforestry plantings, with their systematically spaced trees of near-uniform age and size, are well-suited to the mean tree technique. Biomass estimates within 2-10% of the true value appear realistic based on literature.

The precision of stand biomass estimates obtained by the mean tree technique can be improved by using the basal area ratio method, and by stratified random sampling. Stratified random sampling should be considered if the range of stem sizes is large. In stratified designs, approximately five trees over several diameter classes are sampled. The biomass of each diameter class is calculated separately, and then the class estimates are combined to derive a biomass estimate for the stand. This is a less intensive sampling effort than would be required for the development of allometric equations, but more effort than is needed for stands in which a single mean tree is adequate. If substantially more than five trees per size class need to sampled, the mean tree technique loses any advantage over standard allometric approaches.

The main disadvantage of the mean tree technique is that there is no estimate of the error. This leads to two problems. First, without replication, there is no way to detect a poor estimate. Secondly, there is no statistical method to compare sequential samples. Another shortcoming is that almost all applications of the mean tree technique have been on coniferous species, which tend to be more uniform in shape than deciduous species. Finally, since tree size is related exponentially to diameter, the mean tree technique tends to be biased towards an underestimation of the actual stand biomass. This bias becomes more pronounced as the range of tree sizes in the stand increases.

The largest challenge in using the mean tree technique in the field is to select trees for biomass determination that are truly of average size. This requires careful measurement of stand diameters and simple (yet crucial) math computations that could be a source of error by inexperienced technicians. Second, if subsampling or stand stratification are required, the math and technical problems increase, and more highly-trained field crews are required. However, it should be noted that these problems apply to any method biomass determination used on trees in the field. Biomass measurement is a tedious process. If the trees of a stand have a uniform size and structure and reliable allometric equations for biomass are not available, the mean tree technique may provide rapid estimates of the biomass of the stand.

References

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Madgwick, H.A.I. and T. Satoo. 1975. On estimating the aboveground weights of tree stands. *Ecology* 56: 1446-1450.

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Snell, J.A.K. and J.K. Brown. 1978. Comparison of tree biomass estimators: DBH and sapwood area. *Forest Science* 24(4): 455-457.

Biomass table data collection form

Cruiser ________________ Project ________________ Date ___/___/___

Country________________ Tree species:________________ Biomass or volume (circle one)

				Volume						
				Diameter (cm) or Metric Relaskop (Circle one)			Length (m)	Bark thickness (cm)		
Tree no.	Volume segment no. or biomass component	Stump diameter (cm)	DBH (1.3 m)	D1	D2	D3			Weight (kg)	Comments

Metric relaskop diameter measurements

Distance to tree (m)	Wide strip value(cm)	Narrow strip value (cm)	Distance to tree (m)	Wide strip value (cm)	Narrow strip value (cm)
15	30	7.5	25	50	12.5
20	40	10	30	60	15

D. Plot procedures

1. Navigate to plot center coordinates provided from database, map, map table or Form E.

2. Establish plot center by setting a plot center post (preferably PVC pipe painted with fluorescent paint and marked with the plot number). Flag plot center area to increase visibility.

3. Set DGPS unit up near plot center and collect data for a minimum of 10 minutes (this assumes the base station is already set and is collecting data simultaneously with the same receiver settings).

4. Set digital distance measurer on tripod over the plot center.

5. If the slope is greater than 10%, use a clinometer, Abney hand level or relaskop to determine slope. Correct for slope using the following formula:

$$L_S = L / \cos S$$

where L_S is the corrected plot radius, S is the slope angle in degrees, cos is the cosine decimal taken from the back of the clinometer or from a table, and L is the plot radius.

Note plot dimension corrections on the plot card.

6. The crew chief begins by measuring the distance to the plot edge, flagging the beginning point and directing a technician to begin taking dbh measurements. Each tree should be marked with bright, durable paint at 1.3 m. The top edge of the painted mark should be at 1.3 m. Figure 4 shows the proper placement of the dbh tape. The technician should read out the measurement, which the crew chief should record and check visually.

7. When all of the trees in the plot have been measured, the crew chief must check to see that all of the trees have been measured and painted.

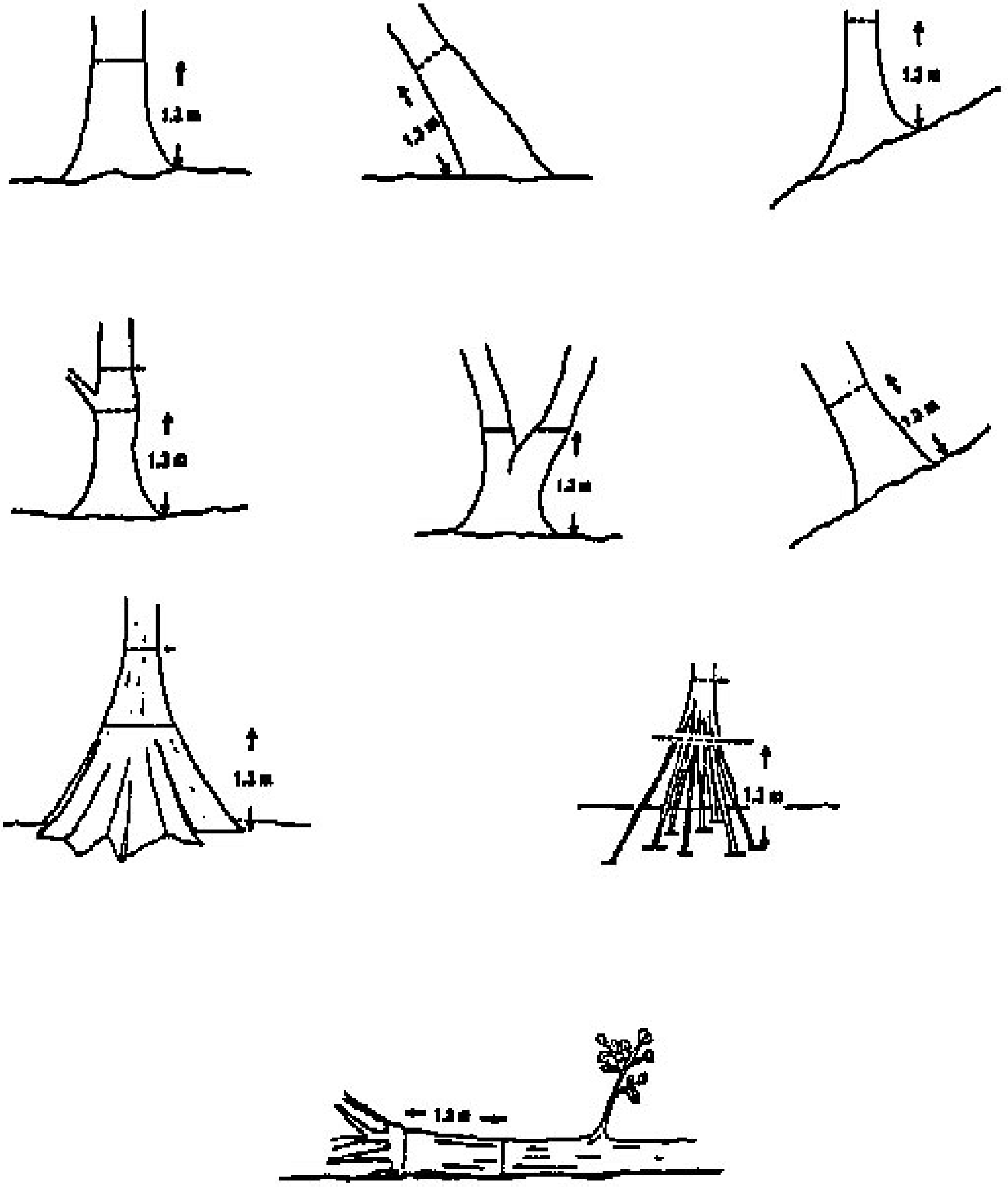

Figure 4. Proper use of a diameter tape

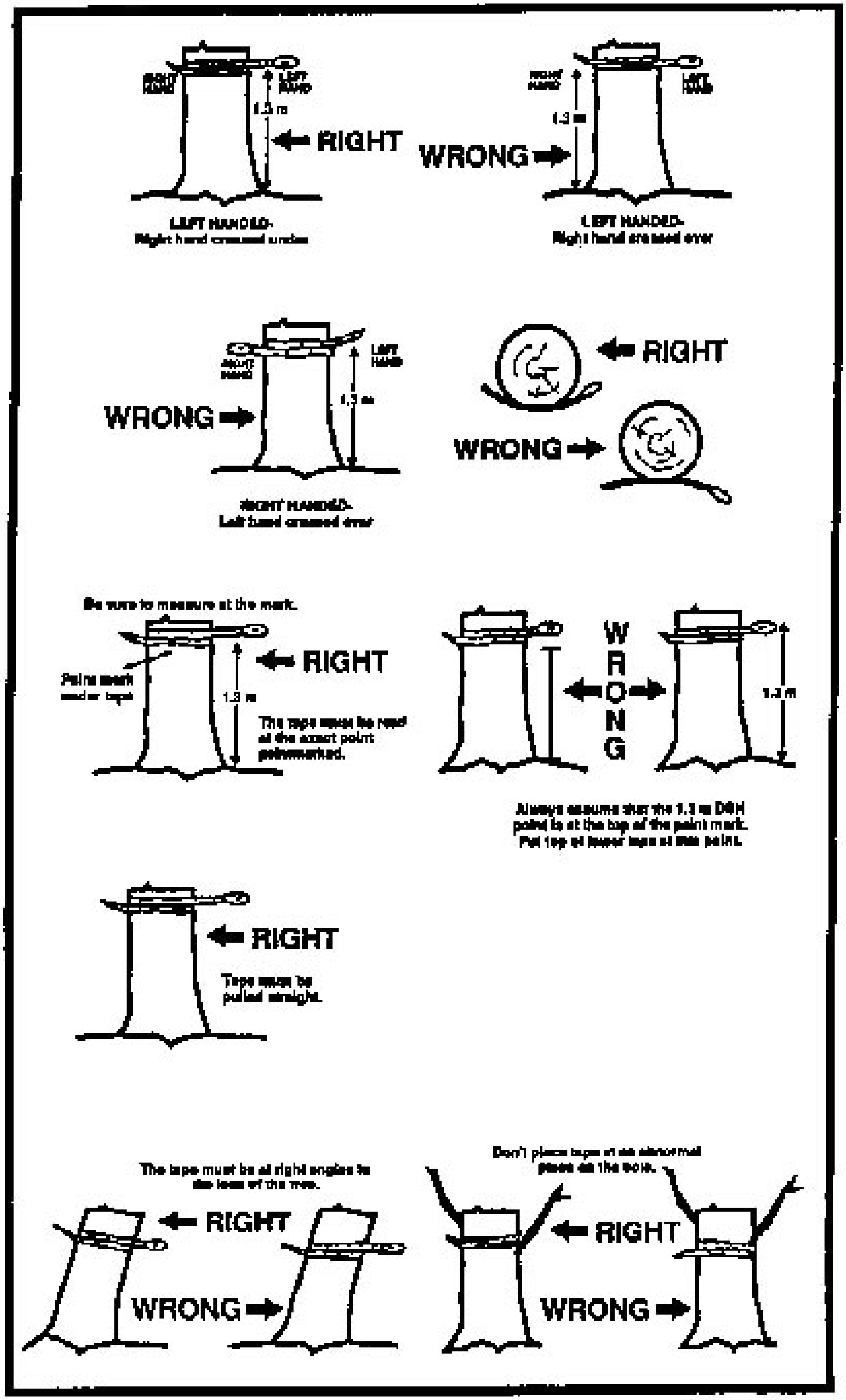

Figure 4 continued.

Appendix 5: Field Procedures for Herbaceous Vegetation, Soils and Standing Litter Crop

The carbon content of soil and litter can be measured and analyzed at relatively low cost if the data is collected at the same time the inventory is conducted. This appendix describes sampling and analysis of carbon in herbaceous vegetation, soil and standing litter crop.

In general, data should be collected in the following order:

1. Herbaceous vegetation
2. Standing litter
3. Soil

A. Procedure overview

1. Go to the northern edge of the plot and select a point 1 m inside the outside edge of the permanent sample plot. This will be the first sampling location for herbaceous vegetation, litter and soils.

2. Lay the quadrat or circular sampling frame on the ground with the outer edge 1 m from the plot boundary. Include in the sample only the vegetation that originates inside the sampling frame. Exclude vegetation over-hanging inside the frame if the plant originates outside the frame, but include vegetation over-hanging outside the frame if the plant originates inside the frame.

3. Clip herbaceous vegetation and small woody vegetation of less than 2 cm dbh, place in the sample weighing bag, weigh, and record the weight. Select a small random sub-sample (e.g., a handful) of this vegetation and place in a numbered sample bag for moisture content determination.

4. Before moving on, collect standing litter from the same sample site, place in the sample-weighing bag, weigh, and record the weight. Mix the sample well and select a small random sub-sample (e.g., a handful) of this litter and place in a numbered sample bag for moisture content determination.

5. Collect a soil core or slice for soil carbon analysis, place this on a plastic tarp, screen with 5-mm mesh, mix well with other cores or slices, randomly select a sample, and place in a numbered sample bag for carbon content analysis.

6. Proceed in a clockwise direction to the next sampling site within the sample plot. From the first sampling location (i.e., North) this will be East, the next will be South and the last sampling location will be West.

B. How many samples to collect

An inventory effort should calculate the number of samples required for a specified level of precision before plot measurements begin. However, if data can be analyzed during the inventory (i.e., using data collected from the previous day's collections), fewer samples may be needed. Use Form C to describe the sampling design for soil organic carbon.

C. Herbaceous vegetation

In permanent sample plots, herbaceous understory vegetation can be sampled using four to six quadrats or circular sample frames per plot. Figure 5 shows three types of sampling frames useful for this type of sampling, although many alternatives exist. The main criterion is that the frames be durable and retain their size and shape over long periods of use. All frames used in a project must be of the same size. Frames with at least one hinge allow the user to wrap the frame around broad canopied plants when necessary. Experience suggests that round aluminum frames with hinges on two sides are more durable than welded square frames, and are also more easily transported.

In plotless quarter-point surveys, one quadrat should be collected at random in each quarter (see Figure 3).

Cut all vegetation inside each quadrat/circular sampling frame at ground level. Take care to cut at the same height for each sample. Clip herbs within the sampling frame in a vertical column extending from inside the sampling frame, so that samples represent the biomass within the frame's area. Weigh biomass for each quadrat and take and weigh a sub-sample for moisture content, and possibly for determining nutrient concentration.

D. Standing litter crop[31]

Changes in standing litter crop can be important, particularly when forest soils are converted to land uses that oxidize organic matter (e.g., crops that require intensive cultivation). It is easy to measure the standing litter crop, but it requires consistent adherence to pre-defined standards.

Measure the standing litter crop by collecting all litter on the soil surface in each of the sampling frames used for measuring herbaceous vegetation. Samples can be bulked by plot. Make sure to record the number of sample frames collected in each plot. Samples should be weighed and sub-samples collected in the same way as for herbaceous vegetation.

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[31] *Standing litter crop* is the total weight per unit area of litter on the soil surface at the time of sampling. *Litter* is organic debris on the soil surface, and is usually freshly fallen or slightly decomposed vegetation. Measurement of the standing litter crop does NOT require monitoring of litterfall.

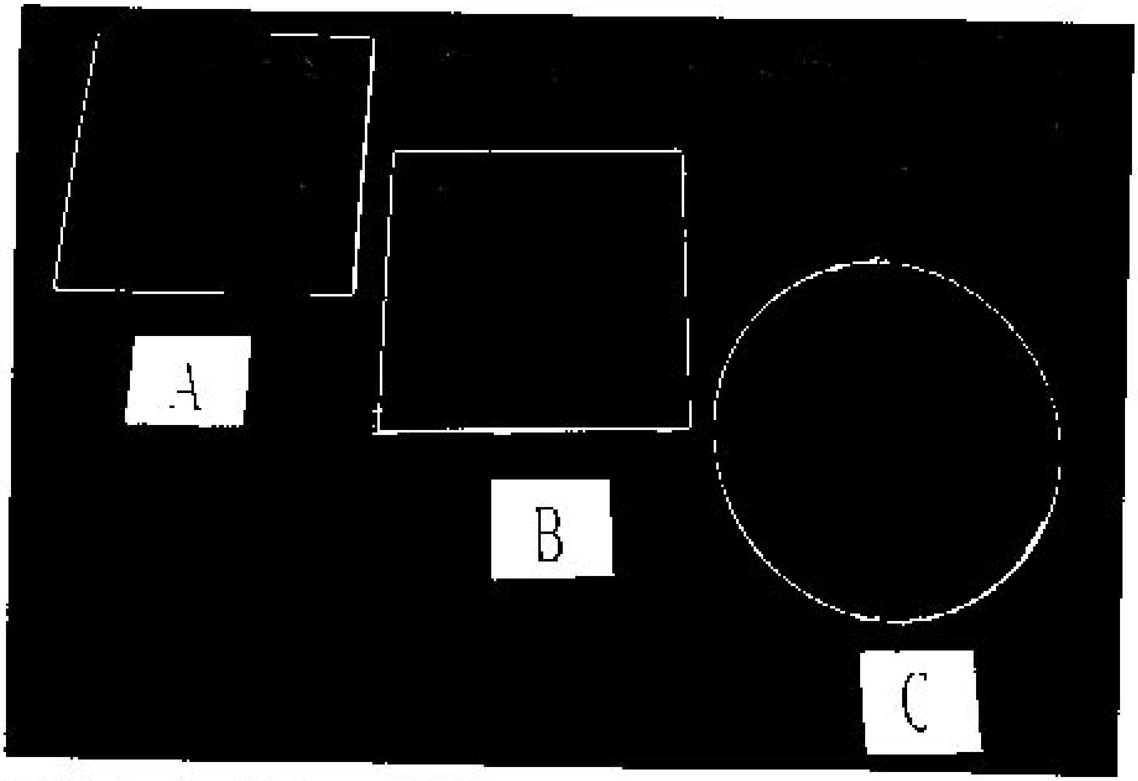

Figure 5 Examples of aluminum sampling frames for herbaceous vegetation and standing litter crop measurements.

E. Soil sampling In general, soil samples should be taken when the permanent plots are established and measured. Use either a soil corer of 30 cm in length or hand-dug pits of 30 cm in depth. A soil corer may provide greater efficiency where soils are not excessively stony, although a folding entrenching shovel (military type) is usually lighter and more versatile. Due to charcoal's high carbon content, it is important to take special care to remove bits of charcoal from samples at any sites that have been burned prior to sampling.

Soil samples should be collected from the 0-30 cm horizon unless otherwise specified.[32] To collect soil samples, remove all vegetation and litter from the soil surface prior to sampling. Place the soil core or slice on the plastic tarp and remove coarse fragments using a 5-mm screen. If multiple subsamples are to be taken per plot, screen all samples on the plastic tarp and mix thoroughly to a uniform color and consistency. Place a sample in a clearly labeled sample bag (preferably a cloth or Tyvek oil sand bag). The quantity of soil required may depend upon the laboratory and analysis to be used; discuss sample needs thoroughly with laboratory technicians beforehand, to ensure that samples are properly prepared and labelled in the field.

To convert total or organic carbon concentrations into total quantities, bulk density of soils is required.

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[32] The greatest changes in soil organic carbon in non-humic tropical soils are often found between the 0-30 cm and >30 cm horizons. For a summary of organic C contents in a wide range of tropical soils, see Table 5.2 in *Properties and management of soils in the tropics*, by P. Sanchez (New York: John Wiley and Sons, 1976).

Bulk density is considered to have relatively low spatial variability,[33] with coefficients of variability of less than 10%. For a uniform soil type, four samples should be sufficient to estimate mean bulk density to within 10% of the true value 95% of the time. The following procedure can be used to determine bulk density with a Modified Uhland soil corer:

1. Identify tin sample boxes and tops, weigh and record as W1 (g).

3. Prepare a smooth surface at a sampling depth of 5 cm.

4. Drive sampler into the soil to fill inner core without compression (use mineral oil if soil-metal adhesion occurs).

5. Trim ends, remove core. If core does not completely fill the cylinder, use glass bead adjustment. If it does fill the cylinder, push contents into sample tin, close tin, mark and record tin number.

6. Place samples in an oven set to 100^{o} C for about 72 hours. After drying, record the weight of the tin + dry soil as W2 (g).

7. Calculate bulk density as: BD (g cm^{-3}) = (W2-W1)/344.77

Soil C content (t ha^{-1} for the 0-30 cm soil depth) = BD * 300 kg m^{-2} * C concentration (%) * 10

F. Deciding what type of soil carbon analysis to do

Soils can contain two types of carbon: organic and inorganic (carbonate). All agricultural soils contain some organic carbon, but not all soils contain inorganic carbon. In most cases, soil organic carbon will be the most important source of soil carbon, although this is not true in arid soils (Aridisols) and several other soil types. Most changes in soil carbon due to project activities are assumed to be in organic matter[34], and not in inorganic carbonate.

Many laboratories routinely use the Walkley-Black procedure for determining soil organic carbon, although it is known to have a number of important limitations. However, because it is commonly used, rapid, and simple, this method is recommended for analysis of soil organic carbon where total carbon analysis is not required. Table 5 compares methodologies for determining soil organic carbon, including Walkley-Black.

If soils are known to contain substantial quantities of inorganic carbonate and the inorganic carbonate fraction is likely to change (e.g., if an arid soil is irrigated), then total carbon methods are necessary. Table 6 provides a summary of the relative quantities of organic and carbonate soil carbon in soils, by suborder, using Soil Taxonomy. Table 7 summarizes methodologies used for determining total soil carbon.

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[33] Warrick, A.W. and D.R. Neilson. 1980. Spatial variability of soil physical properties in the field. In D. Hillel, ed., *Applications of soil physics*. New York: Academic Press.

[34] The average C content of soil organic matter ranges from 48 to 58%.

Table 5 Comparison of methodologies for determining organic C in soils.

Method	Principle	Advantages	Disadvantages
Difference between total C and inorganic C	Total C and inorganic C are determined on separate samples: Organic C = Total C - inorganic C.	Useful if total C and inorganic C are routinely determined	Two separate analyses are required. Total C determination requires special equipment. Organic C calculated by difference has some inherent error.
Determined as total C after removal of inorganic C	Total C is determined in soil sample after removal of inorganic C with an acid pretreatment: Organic C = Total C	Accurate if dolomite is absent from soil	Not all dolomite in soil may be removed by acid treatment. Specialized equipment needed.
Dichromate oxidation without external heat	Dichromate oxidizes organic C to CO_2 in acid medium. Amounts of $Cr_2O_7^{2-}$ reduced is quantitatively related to organic C present. Not all organic C in samples is oxidized when external heat is omitted, and a correction factor is required.	Very rapid and simple. No special equipment required	Incomplete oxidation of organic C necessitates use of correction factors, which often results in erroneous values. Chloride, Fe^{2+} and MnO_4 interfere with method. It assumes soil organic C has an average valence of 0.
Dichromate oxidation with external heat	This is the same as the dichromate method above except that all organic C in the sample is oxidized, and no correction factor is required.	Rapid and simple. Complete oxidation of organic C occurs	Chloride, Fe^{2+}, and MnO_2 interfere with method. Some specialized equipment is needed. It assumes soil organic C has an average valence of 0>

Table 6. Organic and carbonate carbon mass in soils of the world[35]

Suborder/Order	Organic Carbon	Carbonate Carbon	Total Carbon
	---------------- Gigatons of carbon (Petagrams or 1 x 10^{15} g) ----------------		
Folists	1	0	1
Fibrists	250	0	250
Hemists	68	0	68
Saprists	71	0	71
Histosols	390	0	390
Aquands	1	0	1
Cyrands	18	0	18
Torrands	1	1	2
Xerands	2	0	2
Vitrands	1	0	1
Ustands	13	0	13
Udands	33	0	33
Andisols	69	1	70
Aquods	4	0	4
Ferrods	0	0	0
Humods	41	0	41
Orthods	53	0	53
Spodosols	98	0	98
Aquox	1	0	1
Torrox	0	0	0
Ustox	41	0	41
Perox	16	0	16
Udox	92	0	92
Oxisols	150	0	150
Aquerts	1	1	1
Xerets	5	1	6
Torrets	12	14	26
Uderts	5	0	5
Usterts	15	9	24

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[35] Source: Eswaran, H., E. Van den Berg, P. Reich and J. Kimble.1995. Global soil carbon resources in R. Lal, J. Kimble, E. Levine and B.A. Stewart (Eds.). *Soils and Global Change*, CRC Lewis Publishers, Boca Raton, FL.

Table 6 continued.

Suborder/Order	**Organic Carbon**	**Carbonate Carbon**	**Total Carbon**
Vertisols			
Salids	5	113	118
Gypsids	3	12	15
Calcids	17	407	424
Durids	0	1	1
Argids	38	112	150
Cambids	47	399	446
Aridisols	110	1044	1154
Aquults	5	0	5
Humults	4	0	4
Udults	50	0	50
Ustults	40	0	40
Xerults	2	0	2
Ultisols	101	0	101
Albolls	2	0	2
Aquolls	1	1	2
Rendolls	0	1	1
Xerolls	13	23	36
Borolls	15	29	54
Ustolls	17	32	49
Udolls	24	53	49
Mollisols	72	139	139
Aqualfs	6	0	6
Boralfs	35	0	35
Ustalfs	45	71	116
Xeralfs	14	0	14
Udalfs	36	56	92
Alfisols	136	127	236
Aquepts	67	12	79
Plaggepts	0	0	0
Tropepts	20	26	46
Ochrepts	135	247	382
Umbrepts	45	0	45

Table 6 continued.

Suborder/Order	**Organic Carbon**	**Carbonate Carbon**	**Total Carbon**
Inceptisols	267	285	552
Aquents	20	0	20
Arents	0	0	0
Psamments	21	30	51
Fluvents	3	6	9
Orthents	62	81	143
Entisols	106	117	223
Rocky land	13	0	13
Shifting sand	5	0	5
Misc land	18	0	18
TOTAL	1555	1738	3293

Table 7. Comparison of methods used for determining total C in soils.

Method	Principles	CO_2 Determination	Advantages	Disadvantages
Dry combustion (resistance furnace)	Sample is mixed with CuO and heated to 1000 C in a stream of O_2 to convert all C in sample to CO_2.	Gravimetric Titrimetric	Reference method widely used in other disciplines Variable sample size	Time-consuming; leakfree O2 sweep train is required. Slow release of CO_2 from alkaline earth carbonates
Dry combustion (induction furnace)	Sample is mixed with Fe or accelerators and rapidly heated to >1,650 C in a stream of O_2 to convert all C in sample to CO_2	Gravimetric	Rapid combustion High temperature ensures conversion of C to CO_2	Leakfree O_2 sweep train required, induction furnace is expensive
Dry combustion (automated methods)	Sample is mixed with catalysts or accelerators and heated with resistance or induction furnaces in a stream of O_2 to convert all C in sample to CO_2	Gas chromatography Gravimetric Conductrimetric	Rapid and simple, good precision	Expensive equipment. Slow release of CO_2 from alkaline earth carbonates with resistance furnace
Wet combustion (combustion train)	Sample is heated with $K_2Cr_2O_7$ - H_2SO_4-H_3PO_4 mixture in a CO_2-free air stream to convert all C in sample to CO_2	Gravimetric, Titrimetric	Equipment readily available, good accuracy, easily adapted to analysis of solutions, titrimetric analysis of CO_2 less subject to operator error	Time-consuming; gravimetric determination of CO_2 requires careful analytical techniques, titrimetric determination of CO_2 is less precise

G. Sample preparation

This section describes procedures for preparing samples of soil, litter and vegetation for analysis after they have been collected in the field.

Soils

Soils should be air-dried, but not exposed to direct sunlight. Check with the laboratory for detailed arrangements.

Litter and vegetation

After weighing the samples, take sub-samples of litter and vegetation to determine moisture content and nutrient concentration. The following guidelines are suggested:

Moisture content: Mix the sample and collect one random sub-sample of approximately one handful of litter of vegetation per quadrat/circular sample plot. Bulk these subsamples by permanent plot or transect when using the plotless method. For moisture content, collect at least five sub-samples for each vegetation type. Sub-samples should be weighed in the field then returned to the laboratory for oven-drying at 70-80^{o}C to a constant weight and reweighed to determine dry-matter.

Nutrient concentration: This is necessary only if the decision is made to use actual C concentration data for vegetation, or if actual data are to be used to predict carbon pool changes using a computer model. A minimum of five samples for each partition is suggested for C (for carbon calculations only) or C and N analysis (for modelling purposes). This means five core samples of wood (collected at dbh), five foliage and litter samples.

Appendix 6: Measuring Carbon in Agroforestry

These methods are designed for use in agroforestry and farm forestry plantings as described in Section 3. They have been only preliiinarily field tested, and should be used or cited with caution (see *Field Tests of Methods for Monitoring Carbon in Forestry Projects*).

Map the project area.

1) Using current aerial photos, determine the number, size, and location of agroforestry plantings in the project area. If aerial photos are not available, obtain a list of farmers who have associated agroforestry plantings in association with the project and plot the locations of their farms to the extent possible on a topographical map.

2) Use a soils map to stratify the plantings into groups if soil types vary significantly within the project area. If a soils map is not available for the area, consider stratification if there are major differences in topography, drainage, or parent material which affect the suitability of soil for crops or trees. Avoid establishing more than three strata, if possible.

3) Assign a number to each planting within the project area.

Select a preliminary sample of plantings for the determination of required sample size.

1) Using the assigned numbers, randomly select three farms from each stratum. Measure accumulated above- and below ground-biomass in the agroforestry plantings using the methods outlined below. Calculate the variance in the data, and use this value to estimate the number of farms in each stratum that must be sampled to estimate carbon accumulation at the desired level of precision (see Appendix 2).

2) If aerial photos are not available for the region and a preliminary estimate of average agroforestry plantation size was not calculated, then at least six farms must be selected per stratum. The size of agroforestry plantings will be measured on each of these six farms, while three will be selected at random for the measurement of accumulated biomass. As with biomass, the variance in planting size will be calculated to determine the number of farms that must be sampled to estimate the average area of agroforestry plantings at the desired level of accuracy.

Select a sample of plantings for the determination of accumulated biomass.

1) Using the numbers assigned to each farm and the desired sample size calculated in the preceding step, randomly select a sample of farms from each stratum. Make the sample list large enough so that it includes several alternates.

2) The sampling scheme must be nested if aerial photos were not used to provide a preliminary estimate of farm size. First, establish a random list of farms in each stratum that will be sampled for agroforestry planting size. Next, from this list randomly select a sub-sample. Agroforestry plantations on these farms will be sampled for both size and accumulated biomass.

3) Circle the location of the farms to be sampled on an aerial photo or topographic map. Use this map to efficiently organize the sampling effort. Include the names of each farmer on both the map and list of sample farms, if available.

Farmer contact

1) Before initiating field measurements, first make contact with local community leaders and officials. Be prepared to present identification, official letters, or other forms of authorization.

2) Contact a farmer on the sample list. Formally introduce the carbon inventory crew: the names of each crew member, where they come from, their professional titles, and the names of their respective organizations.

3) Describe clearly the purpose of the carbon inventory. Do not avoid explaining why carbon sequestration is important, if asked. Describe the types of measurements that will be conducted.

4) Ask permission to inventory the accumulated biomass of the farmer's agroforestry planting. If permission is not granted, thank the family for their time, and move on to the next farm. Replace the sample from the list of alternates.

Conduct farmer interview (see interview form, this Appendix).

Plot reference point location

1) Prepare a sketch map of the farm's agroforestry plantings on the reference point location form.

2) Walk around the perimeter of the agroforestry planting to determine the location of each corner of the planting with the GPS unit. Record these values on the sketch map.

3) Estimate the approximate length and width of the agroforestry planting. Record the values on the reference point location form.

4) Divide the estimated length and width of the agroforestry planting by two. Record the values on the reference point location form.

5) Locate the southeast corner of the agroforestry planting. Label the location of the southeast corner on the sketch map.

6) Starting at the southeast corner and proceeding along the long side of the agroforestry plantation, measure out a line exactly equal to one half the value of the previously estimated length of the plantation (Figure 6). Use a 100 meter tape to measure this distance precisely. Record the exact distance and bearing of the line on the reference point location form. The endpoint of this line shall be referred to as the turn point.

7) Paint a blue ring at DBH on a tree located along the perimeter of the plantation proximal to the turn point.

8) At the turn point, turn exactly 90 relative to the direction of travel and towards the interior of the planting. Proceed a distance exactly equal to one half of the previously estimated width of the agroforestry planting. Use the 100 meter tape to measure out this distance precisely. The endpoint

of the line shall be referred to as the plot reference point. Record the exact distance and bearing of the line on the reference point location form.

9) Mark the plot reference point with a 40cm section of rebar. The bar shall be driven 30cm into the soil, and the last ten cm of the rebar above the soil surface shall be painted blue.

10) Measure the exact distance and bearing to the plot reference point from two reference trees. Record these values on the reference point location form. The difference between the bearings from the two reference trees should be approximately 90 . Paint a blue ring around each reference tree at DBH, and record the species and DBH of each reference tree on the reference point location form.

11) Determine the coordinates of the plot reference point with the GPS. Record the coordinates on the reference point location form.

12) Once a plot size has been selected, **employ the same plot size on all plots throughout the duration of the biomass inventory**, regardless of the tree spacing encountered on a particular agroforestry planting.

Plot location

1) Refer to Figure 7. If the inventory plot size is 1/20th ha or greater, the following distances and bearings shall be used to locate four plots in relation to the plot reference point (RP):

plot 1 is located 60.0 m from the RP at a bearing of 45 NE

plot 2 is located 20.0 m from the RP at a bearing of 135 SE

plot 3 is located 60.0 m from the RP at a bearing of 225 SW

plot 4 is located 20.0 m from the RP at a bearing of 315 NW

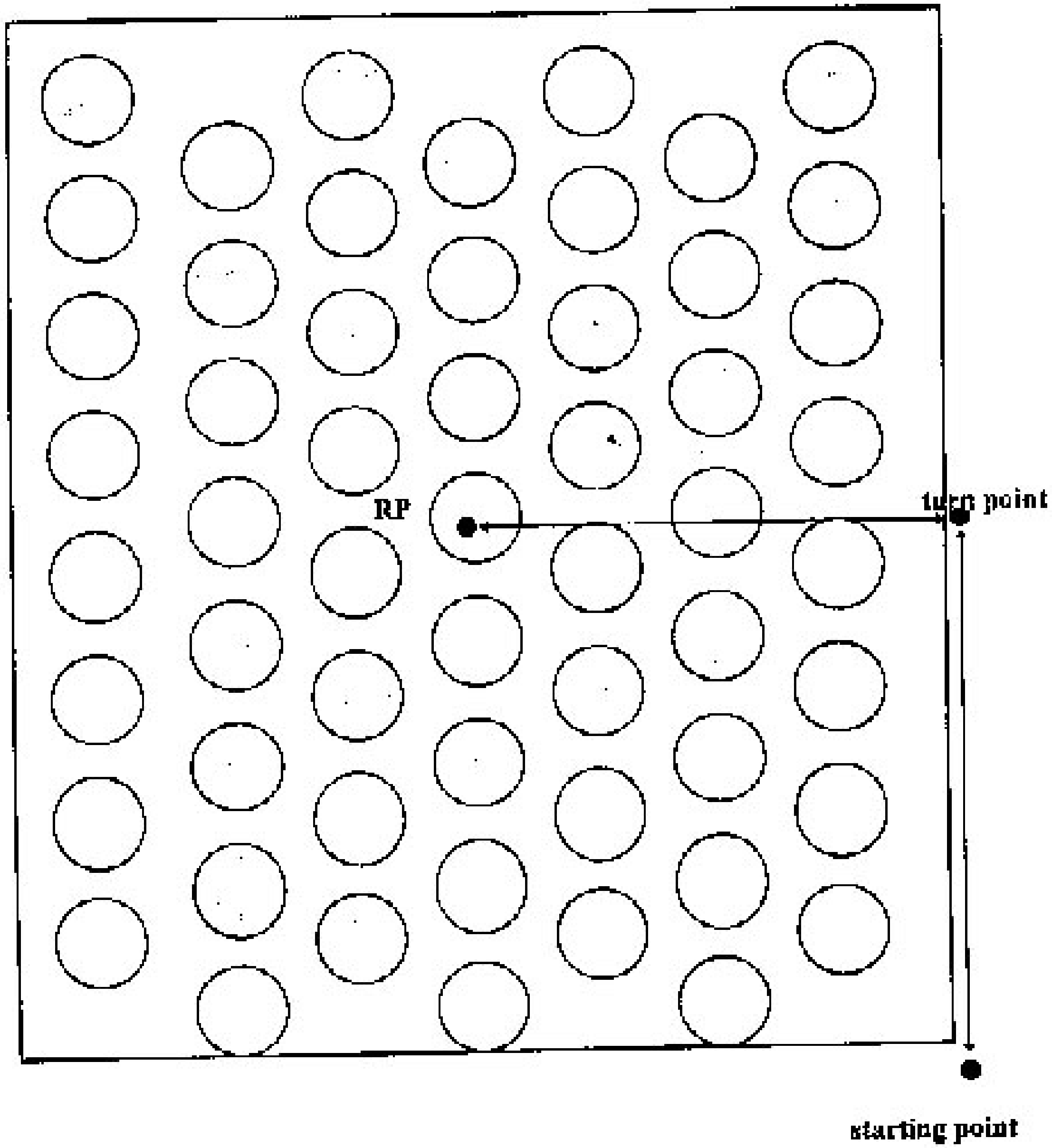

Figure 6. Location of the plot reference point

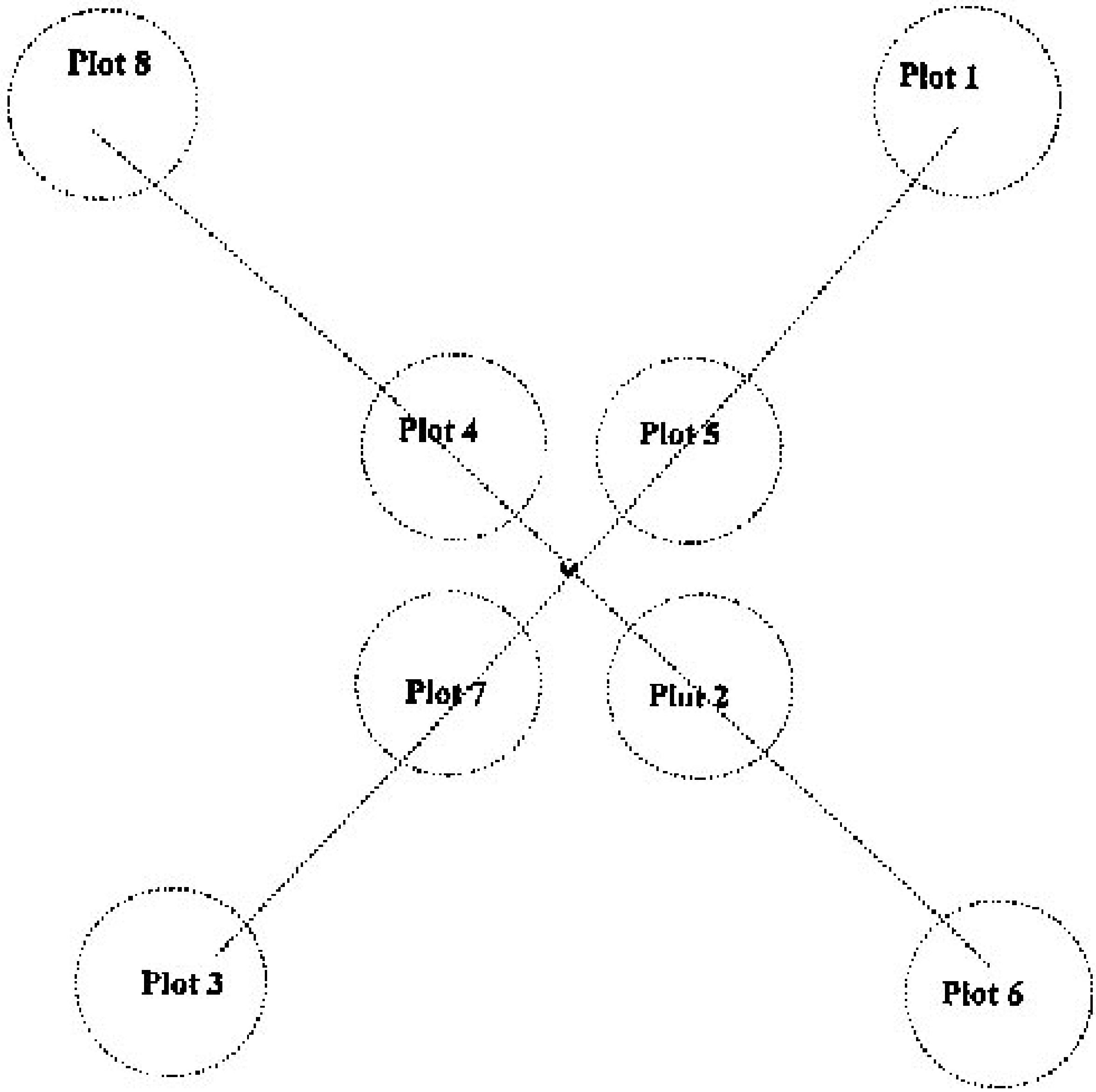

Figure 7. Plot layout for agroforestry/farm forestry inventory plots

2) If the inventory plot size is 1/40th ha or less, use the following distances and bearings to locate four plots in relation to the plot reference point (RP):

plot 1 is located 45.0 m from the RP at a bearing of 45 NE
plot 2 is located 15.0 m from the RP at a bearing of 135 SE
plot 3 is located 45.0 m from the RP at a bearing of 225 SW
plot 4 is located 15.0 m from the RP at a bearing of 315 NW

3) If either the plot center or more than 25% of the plot area is located outside the perimeter of the agroforestry planting, do not establish a plot at that point. Instead, attempt to install a plot at an alternate location. The first alternate is plot 5, falls outside of the agroforestry planting, then the next alternate is plot 6, then plot 7, and finally plot 8.

4) Install the plot rope stake firmly at the center of the plot.

5) Mark the plot center with a wire flag labeled with the plot number.

Conduct an inventory of woody stems >5.0 cm DBH

1) Starting at north and moving clockwise, record the total height, DBH, and species of all woody stems > 5.0 cm DBH that fall within the plot. Record that data on the large stem biomass form.

2) For borderline trees, if more than half the stem falls within the plot, the tree is in; if more than half the stem falls outside the plot, the tree is out. If the plot boundary coincides exactly with the center point of the tree, flip a coin. If heads, the tree is in; if tails, the tree is out.

3) The corrected slope distance should be calculated for borderline trees or for trees just outside the plot if the slope is greater than ~20%. To do this, determine the slope angle from the plot center to the tree in question with a clinometer. Next, multiply the cosine of the angle (provided by the table printed on the side of the clinometer) by the apparent distance. The resulting value is the true horizontal distance. Use this value to determine if the tree is in or out of the plot.

Conduct inventory of herbs, litter, soil and woody stems < 5.0 cm DBH (See Appendix 5)

Limitations

The methods outlined here should be adequate for a wide array of agroforestry system configurations, but they are not appropriate for all types of plantings that may be encountered. These methods are intended for agroforestry systems which: are predominantly square, rectangular, or round in shape; at least 0.25 hectares in size; and have trees as the predominant cover type. Narrow strips of trees, such as windbreaks, would require a different inventory method; so would silvopastural systems in which the trees are widely scattered over a dominant matrix of grass. However, for most situations in which an objective of the agroforestry project is to sequester carbon, this inventory scheme should prove adequate.

Woody stem inventory form

mo / day / year

Crew:______________________________________ date:___/_____/____

Farm number:________________ Stratum number:__________________________________

Plot number: ________________ Plot radius: __________________

Woody stems >5.0 cm DBH

tree number	**species code**	**height**	**DBH**	**tree number**	**species code**	**height**	**DBH**

Farmer interview

Crew:____ date:___/___/___

Farmer's name: ____

Farm number:________________ Stratum number:__________________________________

Farm location:____

Approximate date when agroforestry planting was established:___________________________

Land use of the plot before the planting was established:

_ fallow___ years _ pasture___ years _ crop___ years _ forest

Approximate size of agroforestry planting:____

Reasons for establishing the agroforestry planting:______________________________________

____

Tree component of the agroforestry planting:

species	spacing	number planted	growth rate	problems	products/ yield

Crop component of the agroforestry planting:

species	spacing	planting date	harvest date	problems	products/ yield

Reference point location form

mo / day / year

Crew:____ date:___/_____/____

Farm number:_______________ Stratum number:_________________________________

Agroforestry plantation sketch map

est. length of agroforestry plantation = ______ ÷ 2 = ______ bearing to turn pt. = _______

est. width of agroforestry plantation = ______ ÷ 2 = ______ bearing to reference pt. = _______

	species	DBH	distance to reference pt.	bearing to reference pt.
1st reference tree				
2nd reference tree				

GPS coordinates of the plot reference point = ________________

Appendix 7: Estimating Root Biomass[36]

Estimating root biomass is expensive. Yet, root biomass is an important carbon pool because it often represents 10 to 40% of total biomass. Two general approaches for claiming carbon credit for root biomass are possible: 1) use conservative, non-controversial estimates of root biomass based on literature values for similar vegetation types, and; 2) measure root biomass. The only advantage to measuring biomass for carbon credit is that in most cases, actual root biomass will likely be substantially greater than the conservative estimates. The decision of whether or not to measure should be based on the price of carbon compared to the cost of collecting the additional data required to claim credit.

A. Estimating root biomass using the literature

The data available on root biomass are limited due to the high costs of sampling and measuring roots. However, the literature does contain root biomass values for a wide range of vegetation types. Unfortunately, the methods used vary greatly and the very limited information on vegetation type by site class does not allow high confidence in using actual literature values in most cases. For example, limited root biomass data from tropical forests suggest that the root:shoot ratio varies from 0.03 to 0.49, with below-ground biomass ranging from 11 to over 130 t/ha. The fact that some root biomass exists below living above-ground biomass is undisputable, but the question is, How much? How conservative should estimates using literature values be? In a literature-based approach, the key is to use estimates that are conservative enough so that they are not easily refuted. In the example of the root:shoot ratio in tropical forests, a value of 0.10 or 0.15 would generally suit this purpose.

The level of conservatism required to pass minimum criteria for carbon credit is still undefined. A reasonable approach might be to use the lowest above-ground:below-ground biomass ratios to estimate below-ground biomass, based on actual inventory data of above-ground biomass.

B. Measuring root biomass

If such data are not available, root biomass can be estimated by sampling and measurement using the methods described in the following paragraphs. In measuring root biomass, note the following points:

- Samples should be taken from representative volumes of soil — usually 0-30 cm soil depth unless otherwise specified.

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[36] Portions of this appendix come from Appendix D: Roots: Length, biomass, production and mortality, by M. Van Noordwijk, in *Tropical soil biology and fertility: A handbook of methods*, eds. J.M. Anderson and J.S. Ingram (London: CAB International, 1992) and *Methods of studying root systems*, by W. Bohm (Berlin: Springer-Verlag, 1979).

- Samples should be taken during the time when expected standing root biomass is highest (e.g., avoid the late part of the growing season).
- The methods for sampling, storing, and washing samples will always lead to some loss of dry weight and nutrients. A correction factor of 1.25 - 2.0 should be applied to the final data, with the correction factor based on the estimated losses due to sampling and processing.

Two types of sampling may be required: 1) core sampling to determine root biomass in the 0-30-cm soil depth; 2) monolith sampling to determine relative root distribution beyond 30 cm soil depth. Decisions about the types of sampling required must be site specific and include consideration of precision needs, the availability of data on root distributions for the species being inventoried, soil depth, texture and stoniness.

Core sampling

A soil corer removes a known volume of soil from a known depth in the profile, without the need for digging a soil pit. A core of 50 - 80 mm diameter is satisfactory, and the corer can be inserted either manually or mechanically. Manual coring is difficult at depths greater than 50 cm and in clay or stony soil. In dry sandy soil a smaller core diameter may be needed to reduce losses of soil when extracting the core. In very stony soil, or where there are many woody tree roots, coring may not be possible. In these cases, regular, known volumes of soil (monoliths) can be taken from the face of a pit and treated in the same way as cores.

A commercially available split-core corer, such as the AMS split core sampler kit with core tip, is recommended.

Ideally the profile should be sampled to the limits of rooting depth. At that depth, however, rooting intensity is low and spatial variability high. A meaningful lower limit can be set based on initial observations of the profile wall. In some cases a linear relationship of the log of root mass versus depth (a negative exponential root distribution) may help to extrapolate root densities in the soil beyond sampling depth. All soils must be sampled to a minimum depth of 30 cm.

Root extraction

The best approach to root extraction is to wash roots from the cores immediately upon return from the field. Core samples can be stored in sealed polyethylene bags in a refrigerator for a few days or deep freeze until processed. If deep freeze facilities are not available, samples can be stored air-dried and re-wetted before washing. Losses of dry weight due to the methods used for storage should be checked.

Soil texture, structure, degree of compaction and organic matter content greatly influence the precision and time required to extract roots from cores. The simplest method involves gently washing a presoaked sample over a large diameter sieve of 0.3 - 0.5 mm mesh. The work can be simplified by washing over a combination of sieves: one with 1.1 and one with 0.3 mm mesh. The first sieve will contain mostly roots, the second mostly debris. The material removed from the sieve(s) can then be mixed in water and the suspended material decanted (live roots of most species have a specific gravity of about 1.0). This residue should then be hand sorted in shallow dishes under water to remove fragments of organic matter and dead roots; normally it is better to pick live roots from the sample and leave debris behind in the dish.

Presoaking samples overnight in 5% sodium hexametaphosphate expedites the process of washing roots from clay soils, but the chemical discolors the roots (particularly in soils with high organic matter content) and may disrupt the tissue, making subsequent identification of live roots more difficult. Such pretreatment will also interfere with chemical analyses. Any lengthy washing procedure may alter the element content of root tissue; only a subsample hand sorted with a minimum of water and processed on the day of sampling should be used for analysis.

Classifying the roots

Fine roots are the most important part of the root system for water and nutrient uptake, as they form the largest part of total root length or root surface area. For woody perennial vegetation there is a fairly obvious distinction between the more or less permanent, secondarily thickened roots and the ephemeral, unthickened roots. This functional distinction usually falls somewhere between 1 and 3 mm root diameter. Roots above 10 mm diameter are not adequately sampled by coring. For herbaceous perennial and short-lived vegetation, roots should be separated into <2 mm and > 2 mm classes. In mixed vegetation, separation of roots of different species is difficult and is not necessary.

Sampling intensity

Even in the most homogeneous soils, spatial variability of root density will be high, with coefficients of variation in root weight commonly in excess of 40%. On heterogeneous soils the C.V. may be much higher. This variability implies that many replicate samples are needed if estimates of root weight need to be precise.

It is advisable to obtain reliable information at one or two well chosen situations, rather than non-reliable data on many. Within each treatment plot take at least 3 cores. Within each plot the samples can be pooled. In natural vegetation where there is no obvious strategy for sample stratification, take the cores on random coordinates. Where patterns are likely to occur (e.g,. row crops, alley cropping) stratification should use within row vs. between-row strata.

Monolith sampling

Monolith samples can be obtained with pinboards made by inserting U-shaped, stainless steel pins or bolts in plywood. The size of the pinboard is determined by the vegetation type, based on previous observations, such as rooting depth and distribution and practical considerations. Soil collected with a pinboard is heavy (a sample of 100 x 60 x 10 cm of soil will weigh about 100 kg), so pinboard size should be matched to the means of supporting and moving a full pinboard. Washing away the soil exposes the roots for observation. If a coarse mesh screen is put on the pins before the board is pushed into the soil, this screen can help to keep the roots in their original location while washing the sample. Washing the sample can be facilitated by soaking overnight in water, deep freezing (for clay soils), soaking in oxalic acid (for soils with free calcium carbonate) or soaking in hexametaphosphate, preferably under vacuum. Whatever the pretreatment used, gentle washing must follow.

After washing away the soil: lift the root system on the mesh screen; photograph it (on a black cloth as background); and/or cut it according to soil layers (indicated by string between the pins while washing the sample), depth zones and/or distance to the plant, in order to obtain root biomass and/or root length (see below for root length). To estimate total biomass per plant, root weight density per zone and depth has to be integrated over the relevant volume. Although the pinboard method is more time-consuming than other methods, it gives more information per unit of effort spent. The method's major weakness is that roots may break or be displaced during washing. It is easier to distinguish between live and dead roots via pinboard sampling than in methods where the root system is not sampled in its entirety.

Assessment of root mass

Washed root samples can be stored in sealed polyethylene bags for a short time in a refrigerator, but deep-freeze storage is preferable. Oven-dry the roots and weigh. Next the dried samples should be combusted for 5 hr. in a muffle furnace in 550˚ C and the residue weighed. Results should be expressed as ash-free oven-dry mass per unit volume of soil.