Methods for estimating above-ground biomass of forest and replacement vegetation in the tropics

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Chapter I. Overview and purpose

Natural forests store a large quantity of carbon, and there is currently great interest in assessing that quantity accurately, since when forests are cleared the carbon is converted to carbon dioxide in the atmosphere. My purpose here is to describe the best scientific methods available for estimating carbon stocks in forests and in the vegetation left behind after forest is cleared.

The mass of living organisms in a forest is called the biomass. It is literally and simply the weight of all organisms living in a precisely delimited region, and it could be determined precisely by capturing every living thing and putting it on a scale. But this would involve destroying the forest, and moreover it would be extremely time-consuming. A far more efficient method, with well-established accuracy, is to measure the size of organisms and from their dimensions estimate the weight. Mostly of the biomass in a forest is in trees, and the focus of methods for estimating biomass is measuring the above-ground portion of trees. In contrast, the part of tree biomass that is below ground -- the roots -- is much more difficult to measure (and currently impossible without destroying the forest). For this reason, nearly all inventories of forest biomass refer only to above-ground weight. This is routinely abbreviated AGB, for above-ground biomass.

There are additional components of carbon in a forest besides the trees. Animals and small, herbaceous plants are alive and add to the biomass, but they contribute such a tiny proportion that they are routinely ignored. On the other hand, fallen logs do not count as biomass, since they are no longer alive, but they can contribute a substantial amount of carbon and so often are included in inventories. Finally, there are below-ground components besides roots, and though below-ground carbon can be substantial in quantity, it is so difficult to measure that it is also ignored. Thus, our estimates of carbon stocks will focus on above-ground living trees and fallen logs.

I will also cover here methods for estimating above-ground carbon stores in land where forest has been cleared or otherwise disturbed by human intervention. This is often called the 'replacement vegetation' -- what replaces the original natural forests. Some replacement vegetation resembles forest, for instance plantations or burned or logged forest, and in these, biomass is again mostly in the trees and methods for its measurement are no different than in natural forest. But in many cases, the replacement is agriculture, with few trees, and measuring biomass requires weighing vegetation covering the ground in fields of crops, grasses, or other herbs.

The key to measuring above-ground biomass is to select locations at random and then measure all trees, alive or dead, and weigh ground-cover where there are no trees. In forest vegetation, the sample locations will consist of square plots, usually 100x100 m in size, but smaller where forest patches are smaller. In each, every tree is measured. In non-forest, plots are also square, but only 20x20 m in size, and ground vegetation is harvested and weighed in just 3 m^2 within the 20x20 m square. Tree measurements are converted to biomass using well-tested correlations called 'allometries'; an allometry is any relationship between two or more different size measurements of an organism. In this case, the relevant relationship is between biomass (which cannot be measured quickly) and trunk diameter and height (which can be). Weight of ground vegetation is taken directly, so no allometry is needed. The biomass estimates are then converted to dry weight (the weight without water) and then to carbon weight (very close to half the dry weight).

Measuring trees and weighing grasses is straightforward. The challenging part of estimating carbon stocks over a wide area is selecting locations at random that span natural variation and making sure the sampling area is adequate. These steps require knowledge of the variation in the vegetation coupled with statistical methods for handling variation. An example is most effective at illustrating this point: Many forests vary with elevation, so plot locations should span the relevant elevation range in order to estimate biomass throughout. Moreover, swamp forests are usually quite different from upland forests, so plots should cover both. Finally, if some of the forest has been logged, then sample plots should include it. In the end, sample plots are supposed to produce estimates of biomass in all types of vegetation, and these must then be multiplied by the land area in each type in order to generate the final total carbon stock. It should thus be clear that the biomass sampling program must be combined with good estimates of land cover, based on satellite or aerial sensing, but I will not cover those topics here.

Literature

Following is a short list of important papers covering methods for estimating forest biomass from tree inventory. The most recent papers (Chave et al. 2005, Gibbs et al. 2007) review prior methods and offer an excellent understanding of the best methods now available.

Brown, S., and A.E. Lugo. 1984. Biomass of Tropical Forests: A New Estimate Based on Forest Volumes. *Science* 223: 1290-1293.

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

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, JP., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145:87-99.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., Perez, R. 2004. Error propogation and scaling for tropical forest biomass estimates. *Philosophical Transactions of the Royal Society of London*, Series B 359: 409-420. [as of July 2008, download from http://striweb.si.edu/publications/results.php?scientist=Richard+Condit]

Chave, J., Condit, R., Lao, S., Caspersen, J.P., Foster, R.B., Hubbell, S.P. 2003. Spatial and temporal variation in biomass of a tropical forest: results from a large census plot in Panama. *Journal of Ecology*, 91: 240-252. [download from http://striweb.si.edu/publications/results.php?scientist=Richard+Condit]

Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters, 2: doi:10.1088/1748-9326/2/4/045023. [download from http://www.iop.org/EJ/article/1748-9326/2/4/045023/erl7_4_045023.html]

Gillespie, A.J.R.; Brown, S., Lugo, A.E. 1992. Tropical forest biomass estimation from truncated stand tables. *Forest Ecology and Management,* 48:69-87.

Chapter II. Summary of methods

As a prelude to detailed descriptions of methods for estimating above-ground forest biomass, I first provide a brief summary of the key steps.

A. Personnel

Field teams will consist of 10 people who will work in a single 1-hectare plot at any time, plus a well-qualified field leader to supervise them and be responsible for the field results. Two data entry clerks will be needed for the project duration, along with a part-time database manager (the latter can be shared with other projects). A project leader who is an experienced forest scientist is responsible for all aspects, from site selection, hiring, measuring, to the final data.

B. Plot location

A useful target is to complete 50 one-hectare forest plots plus 25 smaller non-forest plots, with routine statistical analyses used after 10 and then 25 of each to assess variation and confidence and determine how many more plots are necessary. The ideal plot network would be a perfect grid of plots every 5-10 km, so that location is completely random relative to local terrain. This is the way the U.S. Forest Service samples forests in North America. The flaw is that it might be unnecessarily expensive and difficult to follow this approach where roads are few or terrain rugged, both likely conditions in tropical forest. The alternative is stratified sampling across forest and non-forest and other important variation in vegetation; since forest structure typically varies with rainfall, major differences in soil, drainage, and with human intervention, plots should be chosen to span variation in those features. This becomes possible with remote sensing along with digital climate and terrain data that produce precise maps, which can be reviewed by local biologists familiar with forests of the region. If maps are unavailable and variation in forest structure poorly known, the only recourse is to randomly place plots throughout the area.

C. Forest plot inventory

Forest plots should in nearly all cases be 1 hectare in area, 100x100 m in size. Within each, all trees ≥ 100 mm in trunk diameter are measured, and a smaller sample of trees ≥ 10 mm but < 100 mm are also. In addition, a subsample of tree heights are measured, and a subsample of trees are cored for estimating wood density. There are precise published formulae relating diameter, height, and density to tree biomass, so these data are converted into an estimate of the above-ground biomass in each hectare of forest. In addition, fallen logs are counted and measured in order to estimate dead wood mass.

Tree height and wood density are measured in a random subset of trees from each plot for use in the formulae estimating biomass. In addition, surveys of dead trunks on the ground are necessary for measuring their carbon stocks.

D. Non-forest plot inventory

Any vegetation where natural forest has been removed or severely degraded is here defined as non-forest. Plantations can be sampled just like natural forests, given that they most of their carbon is in trees. Moreover, heavily degraded areas invariably include remnant patches of forest, often along streams; these should be sampled using the forest plot methodology, though plots may have to be much smaller. Agricultural land, pasture, grassland, or shrubland, though, must be sample much differently. Plots of 20x20 m should be used, with ground vegetation fully cut, dried, and weighed in three 1x1 m subplots.

E. Data entry

All data should be entered twice, by two different clerks. This eliminates transcription errors between field sheets and the database. Specialized software for data entry is ideal to facilitate rapid typing and to catch errors. Problems and questions will arise during data entry, and the software will compile these to report to field leaders. Many will require returning to the field to check erroneous measurements, if this is possible.

Use of field computers to record forest measurements is becoming widespread, and these can replace data entry clerks. There remains debate about the relative merits of paper vs. computer recording. The methods I describe here assume the former, with paper forms with clerks transcribing the data in an office. But updated editions of these methods will undoubtedly switch to the use of field computers.

F. Validation

I consider two levels of validation. Self-validation means that the same field workers and supervisors collecting the data review their own measurements. A random sample of trees should be remeasured to assess accuracy of diameter and height data, and likewise some plot corners should be resurveyed. These should be standard practice in any forest plot mensuration. The second level is external validation, meaning review by an independent forestry team. In the methods I present here, I do not include suggestions for details of an outside evaluation, because that would defeat the purpose of independence. The agency behind the entire project along with the team leader should seek scientists with no stake in the project and invite them to visit and review methods and data. Ideally, sufficient funds would be provide to allow these scientists to visit field sites and make independent measurements, and all raw data should be made available to them.

G. Statistical analysis

The goal is finding total above-ground biomass over an entire region. This will include a single best estimate, plus a probability distribution of alternative estimates. If plot locations were truly random over the region, the best estimate is simply the mean carbon per hectare times the number of hectares in the region. But if plots are stratified across variation in terrain and vegetation, the analysis requires fitting that variation (biomass as a function of elevation, climate, disturbance, geology), then using the digital maps of the region. The probability distribution of alternative estimates can be generated with either a Bayesian statistical approach or bootstrap methods, both considering all components of error (tree measurements, allometric models, plot locations, land-use maps). In this document, I provide the formulae for calculating biomass, but only an overview of how to estimate errors; I will aim to provide software for the latter with later editions.

Chapter III. Personnel and training

Getting accurate and defensible estimates of forest biomass obviously hinges on the personnel, including those working in the field, entering data, and directing the work. My key recommendation is to assure that there is one leader for each field team who is competent, reliable, and demanding. Fluency with both the local language and English, ability to supervise the field crew, experience measuring trees, and broad understanding of the data are the ideal abilities required. The next priority is the project leader, the one supervising these field leaders: ideally, an experienced PhD in forest science supervises the field leaders and oversees the entire project.

A. People

1. A field crew. A single crew includes those working in one forest plot at any one time. They are responsible for surveying the plots and measuring the trees. My preference is to work in pairs at all times (with surveying requiring two pairs), with one person making measurements and the other carrying tags and recording. In different parts of the world, however, social preferences about group size are strong, and the field work can proceed with teams of 3 or 4, or even solitarily. The methods section that follows assumes a field crew of 10 people, working in five pairs in a 1-hectare plot at any one time.

The key element of the field team is the leader. This person is in the field every day checking on each of the teams: answering questions, solving problems. The leader should understand the project and thus be qualified to make decisions about unexpected circumstances, but of course reports to the overall project leader. A good leader needs to be demanding of the field workers while also being comfortable with them and understanding their needs.

The single most important trait that the leaders should have is dedication to the project: a deep personal desire to see it succeed. This is crucial because the field crew are always paid workers whose only bottom-line is employment; team leaders must feel ownership of the results. This may be best accomplished by involving students or other young scientists who have a stake in the project, perhaps as PhD theses or authorship on reports.

There may be more than one field crew working at a time, each in a different plot. If so, each needs a field leader. The project can obviously proceed more rapidly with more teams, but the administrative burden becomes heavier. In assessing progress below, I assume two crews of 10 working at the same time.

2. Camp assistants. Plot measurement work will require the field teams to be in one forest plot for 5-6 days. Depending on plot location relative to nearby towns or roads, this may be best accomplished by making camps in the forest. If so, assistants who carry gear, make camp, and prepare meals are most likely going to be involved. This needs to be decided by the project and team leaders.

3. Data entry. Two data entry clerks are needed for the project. Each will enter all the data. Someone with a biology background and experience with forest data would be ideal. But in my experience, data clerk seldom have forestry background, just typing skills and the patience to be careful about numbers; they never go in the forest and do not know how trees are measured.

There should, however, be a supervisor for the data entry clerks. An ideal option is to have a database manager who is a programming and data modeling expert. This person is responsible for working the data entry software, handling data during error-screening, and producing the final database. For a single project of about 50 forest plots, however, this is not a full-time job, so the data manager could be someone shared with other projects. Alternatively, the project leader could take this role, depending on background and interest.

4. Project director. An experienced scientist must oversee the entire project. As for the field team leaders, this person should be someone with a professional stake in local forest biology and conservation, and should have intimate knowledge of local forests and customs. Ideally, this would be a professor at a local university, a staff scientist in a local forestry department, or perhaps a PhD student or post-doc from the area. If none of these options are plausible, the funding agency behind the project may have to bring someone in from elsewhere, or provide the leader from their own staff. Depending on circumstances, the project may or may not have to provide salary support for this leader.

5. Forest experts. Someone involved has to be an expert on local forests: where there are trails, who owns the land, and how the forest varies. Most often, the project leader and the team leaders provide this knowledge. If not, the project leader needs to understand where to get this information, consulting local land owners or other forest biologists where needed.

B. Training

The project begins with the director and field leaders reviewing the methods to be sure they understand all steps in the field data collection. They should also review scientific literature on forest biomass in order to understand the methods (Chapter I). Training sessions should then be set up with the full field crews in easily accessible forest and non-forest areas, perhaps in an experimental forest at a university.

1. Measurements. Field leaders and the project director should initially measure and mark about 20 test trees. These measurements should be deliberately chosen from easy to difficult. Supervisors then present methods to the field crews, and field workers measure the 20 test trees and compare with the supervisors' results; discrepancies should be reviewed and discussed. Then the field workers should measure all trees in a test quadrat of 20x20 m, with supervisors nearby to check results and answer questions. These tests and reviews will help supervisors assign roles to all the field workers.

2. A test plot. A single forest plot and a single non-forest plot should then be undertaken at easily accessible locations. All the methods presented in the following chapters should be followed precisely, and the results should be considered useful, but the main point is to go through all the steps at an easy-to-work site with the project director present. At the end of each day of work, an hour should be set aside for the leader to discuss problems with the entire field crews.

3. Data entry. The clerks to enter data need to be shown the software for data entry, and should spend a day entering test data with the plot director and data manager present to answer questions.

Summary on personnel and training

The key to the project are the director and field leaders. They must understand the project, know the region and the workers, and -- most important -- feel a stake in the success of the work.

Experts in local forests must be consulted.

Field workers preferably are experienced in local forests and have some science background.

Thorough training sessions should be arranged where measurement methods are practiced.

Assuming two field teams working simultaneously, the project thus includes 1 director, 2 field leaders, 20 field workers, 2 data clerks, 1 database manager (half-time), 4 camp assistants (if needed), plus 1-2 consultants on local forests (if needed).

Chapter IV. Site selection

The difficult aspect of placing sampling plots is the variation in vegetation which leads to variation in above-ground-biomass. The goal of the sampling is to properly capture that variation so that an unbiased estimate of the total biomass in the region can be generated. There are three separate issues: the size of each plot, the number of plots, and their spatial arrangement.

A. Plot size inside forest

Plots of 100x100 m, exactly 1 hectare, have been so routinely used in tropical forest inventory that the size has become a standard. It is an appropriate size for assessing stem density and biomass, so I recommend its routine adoption. For statistical rigor, every plot in areas of extensive forest (spanning more than several hundred meters in size) should always take this size and shape. The details of sampling within the hectare-sized plots will be covered in Chapter VI.

B. Plot placement inside forest

Below I consider two alternatives for randomly choosing plot locations in a forest. Regardless of which method is chosen, though, it is very important that the coordinates for each plot should be established from studying maps of the region, without looking at the forest. This helps assure rigor in the statistical analyses: choosing plots by walking through the forest raises the possibility that locations will not be random (avoiding areas that are hard to work, or selecting attractive and tall forest). In Chapter V, I return to this point and cover details on how to use the predetermined coordinates to place the base stake of each plot.

The two alternatives for selecting sites of 1-ha plots in forest are 1) completely random placement over the entire region, or 2) stratified randomly across anticipated variation in the forest.

1) *Random placement.* To make a completely random sample, the entire area of forest under study must be delimited precisely, ideally from satellite or aerial photos. An ideal plot arrangement then would be accoumplished by placing plots on a rectangular grid across the region. For example, if the number of plots desired is 100, a grid of 10 plots x 10 plots should be spaced at a distance that would completely cover the area. (A regular grid is not random, but should place plots independently of spatial variation in biomass, so accomplishes the purpose; calling it haphazard rather than random might be more precise.) This is how the U.S. Forest Service does its regular Forest Inventory and Assessment. An alternative approach would be to literally choose random numbers from within the latitude and longitude of the sampling region. With either method, there is no backing down: locations are chosen without seeing the forest (except on maps), and once chosen, a plot is placed at each site regardless (see further details in Chapter V).

The random selection method is easiest to justify statistically. It assures an unbiased estimate of the regional biomass. The number of plots thus placed sets the error in the estimate, which will be considered in section C of this chapter.

2) *Stratified random.* There are important drawbacks to a truly random (or haphazard) arrangement of plots. In large regions of remote forest -- typical of many tropical sites where biomass assessment is needed -- it would lead to exceedingly impractical locations. Sites chosen might be accessible only after days of hiking, or by helicopter, both greatly inflating the project's expense. For this reason, I consider here sampling based on advanced knowledge of variation in the environment which is known to be relevant to forest structure. Networks of roads, rivers, and trails are used, and plots carefully spaced to span gradients of terrain, climate, and human disturbance. This approach is considerably more complicated: it requires background knowledge and accurate maps. In the accompanying box, I

give three main lines of justification for stratified sampling.

The goal of a stratified sample is to allow plots to be within 3-5 km of roads or rivers while still sampling the variation in forest structure. Sites must be chosen to span elevation and climate gradients in a continuous manner. If some of the forest to be sampled has been logged or trees otherwise removed, then plots need to cover both disturbed and undisturbed forest. Finally, biologists or geologists familiar with the region need to judge whether there are regions of soil or drainage conditions that might cause variation in forest biomass. The proportion of plots placed across various types of terrain must reflect their relative area. For example, if 90% of the region is below 1000 meters in elevation, then 90% of the plots should be below 1000 meters. This means that very rare types of terrain can be ignored or very sparsely sampled. If swamp forests, for instance, cover < 1% of the region, they are not worth including.

A key concern in choosing plot sites using roads or rivers for access is that a bias could result due to human influence. Sites within 1 km of roads or rivers should always be avoided. Further, biologists familiar with the forest need to evaluate carefully the impact of roads. The plots could in fact be arranged to test this question: at what distance from forest roads is biomass affected?

Box 1: Knowledge required for a stratified sampling design
First, it is well-known that vegetation everywhere in the world responds to five major features: elevation, climate, soil (or geology), drainage, and human disturbance. Other factors certainly can have effects, but if a system of forest sampling plots covers most of the variation in these features, it almost certainly spans the range of variation in forest biomass.
Second, knowledge of these major features is widely accessible, even in remote regions: excellent maps of vegetation, terrain, and climate are now routinely available. Satellite and aerial sensors produce images that accurately delimit forest, and digital rainfall and elevation data can be accessed for anywhere in the world. Moreover, there is reasonable general knowledge of forest structure and species composition for forests everywhere. In this document, I am not treating at all the methods for creating maps of vegetation and terrain; instead, I assume that they are available and can be used for designing a stratified sampling design.
Finally, forest biomass varies remarkably little all over the world. In 12 very precisely measured inventories from all continents, spanning a wide range of elevation and climate and including old-growth as well as logged forest, biomass was always 174 to 541 tons per hectare (see the paper by Chave et al., 2008, listed in literature section of Chapter I). This greatly reduces the error in biomass estimates from within a region, even if there is substantial variation in terrain and climate.

3. *Deciding: random vs. stratified*. I recommend using the completely random approach if the forest to be sampled is smaller than about 10-15 km across, or if there are many roads and villages across a larger area that make access to nearly all parts of the forest fairly easy. That is, if any part of the forest can be reached on foot within a day, a random design is best. In contrast, in large forests where there

are few roads (a condition which is likely to hold in tropical regions where there still is a lot of forest), a stratified sampling using roads or rivers for access should be designed.

C. Plot number inside forest

I address this issue here by evaluating the variance in biomass across hectares in well-sampled forests. Within 50-hectare inventory plots in Panama and Malaysia, I randomly placed 200 square hectares following the sampling design and calculations described in the following chapters. In both cases, biomass per hectare has a Gaussian-like distribution, with a clear mode and no extremes (at Barro Colorado, all hectares are within 2.5 SD of the mean, while at Pasoh, all but 2 are); moreover, there was no spatial autocorrelation in biomass. This means that standard, parametric Gaussian statistics can be applied to evaluate variances and confidence: standard deviations can be used to predict the sample size needed to achieve a desired error (since the standard error of the mean declines with the square root of the sample size). At Barro Colorado, a sample of 10 plots of a single hectare would reduce the sampling error to 5% of the mean; at Pasoh and Lambir, it would be 7 and 16 plots respectively (Table 1). These samples would produce 95% confidence limits around the biomass estimates of ± 10%. To narrow these confidence limits to ± 5% would require four times as many plots.

But these are homogeneous forests, and all sample plots are within 1 km. In central Panama, a network of 1-ha plots has been established over a distance of 100 km, ranging in elevation from near sea level to about 1000 m, and including old growth as well as mature secondary forest. In these plots, the mean and SD of biomass per ha were 232.7 and 37.3. In fact, this SD is just 16% of the mean, the same as at Barro Colorado.

Table 1. Variation in above-ground forest biomass from intensive plot inventories in tropical forest

			standard deviation	
site	plot	AGB (ton/ha)	1-ha subplots	20x20 m subplots*
Barro Colorado, Panama	one 50-ha	260.0	41.2	205.6
Pasoh, Malaya	one 50-ha	303.6	40.1	164.9
Lambir, Borneo	one 52-ha	433.7	84.3	229.0
Panama Canal region	36 separate 1-ha	232.7	37.3	126.2
* adjusted to one hectare				

Barro Colorado data available at http://ctfs.si.edu/datasets

Pasoh data from the Forest Research Institute of Malaysia and N. Supardi (Manokaran *et al*., 1992)

Lambir data from the Sarawal Forest Department and S. Tan (Lee *et al*., *2003*)

Panama Canal data available with Condit *et al*. (2002)

On this basis, I conclude that a sample of 25 1-ha plots in mature, upland forest in a region on the order of 100 km across where climate and elevation do not vary much will produce an estimate of above-ground biomass with an error of 10%, or better. If there is heterogeneity in the forest, or climate and elevation vary, I suggest aiming for 50 plots distributed across these gradients.

D. Plot size in non-forest vegetation

I consider here four major types of vegetation that could be found in land classified as non-forest, and discuss first sampling variation and then how many sample plots might be anticipated in planning an inventory. In all cases, the actual number carried out will have to be adjusted depending on preliminary data.

1) Forest remnants. After clearing forest for agriculture, there are most often some stands of trees left behind. Where trees form a complete canopy, the vegetation should be sampled with forest-style plots, as described in Chapter VI. But since remnants of forest may often not be 100 meters in size, I recommend that all sample plots in this type of forest by 20x20 m (0.16 ha).

2) Plantations. Dense stands of trees planted for harvest (teak, oil palm, rubber) should be handled exactly as forest remnants are. Again, I suggest a consistent plot size of 20x20 m in plantations, given the possibility that some might be small in area.

3) Grassland and cropland. Here I refer to the biomass of herbaceous plants and small shrubs in grassland or farmland. This must sampled using very different methods: rather than measuring individual stems, entire aliquots of cut vegetation are weighed. For this reason, plots should be 20x20 m, with subsamples of 1x1 m fully measured (see Chpater X).

4) Isolated remnant trees and fence rows. Grassland and cropland invariably include some scattered trees, sometimes left for shade or in fence rows. These are likely to be difficult to sample accurately due to great variations in spacing between trees. Moreover, this variation means that plot size cannot be determined in advance.

For these reasons, biomass in scattered trees is best estimated using aerial photographs of sample regions of cropland, shrubland, or grassland. On photos, the number of visible trees over specified areas should be counted. A random set of these trees should then be visited in the field, and height and diameter measured. Trees planted in lines along roads, trails, or fences should be sampled similarly. Individual trees should be counted from aerial photos along set lengths of road or fence, then trees chosen at random measured in the field.

Table 2. Estimates of non-forest vegetation biomass.

site	AGB (ton/ha)	vegetation	reference
Cedar Creek, Minnesota, USA	3 ± 1.5[a]	grassland	Tilman & Downing (1994)
Panama Canal area	46	grass only (*Saccarhum*)	Hooper et al. (2002)
Panama Canal area	220 ± 22.3[b]	small forest remnants	Lezcano (2002)
Panama Canal area	98 ± 47.5[b]	teak plantation	Kraenzal et al. (2003)
generic tropical	22	grass-dominated savannah	Scholes & Hall (1996)
generic tropical	40	savannah	Scholes & Hall (1996)

[a] SD among 0.1 m^2 plots; below-ground biomass was 6 tons per ha

[b] SD among 1 ha plots (*N* = 2)

[b] SD among plantations of 48 trees (*N = 4*)

E. Plot location in non-forest

The plots whose sizes were just described now need to be placed at random in regions of the five vegetation types described. As for forest plots, coordinates for plots should be chosen from maps, without going into the field, and locations can either be purely random placement or they can be stratified random.

Under strictly random placement, both forest and non-forest plots could be located at the same time, choosing an arbitrary grid size over the entire region. At each grid point, the plot placed depends on the vegetation located there. Again, this method is ideal statistically, and should be feasible in fairly small regions with reasonably easy access throughout. But in large and remote areas, random placement may not be feasible.

Under a stratified sampling approach, a map is needed to define the non-forest vegetation units. Within each, plots must be placed randomly, always spanning the elevation, climatic, and soil variation within the unit.

F. Plot number in non-forest

An adequate sample for estimating biomass of non-forest vegetation is not so easy to anticipate. The first difficulty is that biomass density can vary enormously across vegetation that is typically called 'non-forest', which usually means a matrix of agriculture and remnant forest. Moreover, the total regional biomass cannot be predicted easily: in intensively managed agriculture, the standing AGB is most likely < 10 tons per ha, but in a matrix including tall grass and many trees, it could be > 50 tons. On the other hand, since the total biomass in non-forest is considerably less than in forest, sampling intensity can be reduced in proportion.

Suggestions for the number of sample plots needed in each of the five vegetation units that I defined in non-forest vegetation

1. Forest remnants. Since plots in small forest fragments need to be small, only 20x20 m in size, sampling variance between plots will be higher than in the forest. But since forest remnants have far less biomass than the intact forest, I suggest an acceptable sampling error would be 15% of the mean (instead of 5%, as in forest). This would about 20 to 25 plots (Table 1). This assumes remnant forest has a variance similar to old-growth forest, but this can be tested once data are collected.

2. Plantations. I have not found studies on local variation in plantation biomass, but since trees are deliberately planted in a regular way, it should be considerably lower than in the forest. I suggest starting with just 10 20x20 meter plots then evaluating the need for more, depending on variation and also how much plantation land there is.

3. Grassland or cropland. Herbaceous or shrub vegetation has much less biomass than forest, so sampling need not be as thorough as in forests. The sampling design (Chapter X) will include three plots of 1x1 m at corners of a 20x20 m quadrat, each to completely harvested of small vegetation. I suggest a sample of ten such 20x20 m sites, or 30 individual meters-squared. This number can be adjusted upward if the variance or the total grassland biomass in the region warrants.

4. Isolated remnant trees. Because the total biomass in these trees is likely to be very low, sampling does not need to be intense. I suggest planning to measure 100 individual pasture trees, chosen at random using aerial photos.

5. Fencerow trees. Likewise, I suggest measuring a random sample of 100 fencerow trees.

Table 3. Recommended plot size and number

Vegetation	Plot size (lengthxwidth in meters)	Plot number
Forest (homogeneous or < few thousand ha)	100x100	25
Forest (heterogeneous or > few thousand ha)	100x100	50
Forest fragments (in non-forest matrix)	20x20	25
Tree plantations	20x20	10
Grassland	1x1	30
Isolated trees	none*	100*
Fence row trees	none*	100*

* 100 individual trees chosen at random from aerial photos

Summary on site selection

1) In regions where access throughout is not difficult, plot sites can be chosen from a purely random design
2) In remote areas with difficult access, a stratified design should be followed, with plots placed randomly in each vegetation unit
3) Within forest, plots should be stratified across elevation and climatic gradient, soil types, and in both pristine and disturbed (or logged) forest
4) Data on climate plus satellite or aerial photos will be needed to define gradients
5) In all cases, plot coordinates should be chosen in advance, before visiting a location
6) Plot size for each vegetation type is determined by sampling considerations and the distribution of vegetation
7) The number of plots should be chosen based on consideration of variance and acceptable sampling error; existing forest plots offer initial guidance
8) The summary table above summarizes recommendations for plot size and number.

Chapter V. Surveying the plots

In order to accurately assess biomass over a large region, precise measurements have to be made in plots, and these averages multiplied by total land area. Obviously, then, the final accuracy hinges as much on measurements of plot area as they do on biomass: a plot of 1 hectare needs to be precisely 1 hectare. Surveying has to be done rigorously.

The first step is establishing a base stake: the origin of the plot. In most cases, I recommend making this the southwest corner. From there, a precisely square plot of a predetermined size will be surveyed, with stakes placed at regular intervals to allow mapping of the trees.

A. Placing the base stake

In the previous chapter, I described methods for choosing random plot locations from maps. Based on these choses, I assume that a set of precise latitude-longitude pairs are now ready to be taken in the field. As I write in 2008, GPS (Global-Positioning-System) are so accurate in the forest that finding a predetermined coordinate within a few meters is routine (I recommend the Garmin 60CSx, which is inexpensive and works adequately under forest canopy.) When the GPS locates the chosen coordinates, one of the marking stakes (described below) is placed in the ground.

For the sake of statistical rigor, I also suggest that all plots be oriented north-south, with the base location in the southwest corner. In all subsequent maps and discussion, I assume this orientation, and in all maps below, north is up.

Before proceeding, though, I have to acknowledge the possibility that a site chosen from a map will be inaccessible or impossible. Perhaps the route from a trail or road to the plot site is cut off by a canyon, or there are illegal mining camps in the area. If a situation every arises where a proposed access route turns out to be impossible, then either a different access route must be found, or the plot site abandoned. In addition, the plot site itself may be accessible, but something within the proposed boundaries -- a steep cliff, canyon, or village (whose occupants may not appreciate plot stakes in their yards) -- may make the location unworkable.

When this situation arises, I recommend a precise protocol for avoiding the barrier: First move exactly 100 m north from the base location, and see if a plot could be placed there. If not, try again 200, 300, 400, and 500 m north. If none of those locations are plausible, return to the original base, and try locations 100-500 m due east. If none of these 10 alternatives works for a plot, the location must be abandoned.

If a proposed plot location must be abandoned, then field workers should proceed to the next predetermined location. A replacement location should not be chosen in the field, rather, another random set of coordinates needs to be selected from maps back in the laboratory. The plot site should only be avoided if it is absolutely impossible! It cannot be passed over simply because it does not look right or seems difficult. Moreover, and this is important, it should not be passed over based on the vegetation. If it is supposed to be a forest site, but lacks forest, the sampling should continue, though plot size should be adjusted based on the recommendations of Chapter IV.

When a location is chosen and the base stake placed, precise GPS coordinates should be recorded.

B. Avoiding damage

The purpose of the surveying is to demarcate a plot where live trees and dead logs will be counted. The survey team needs to take care not to cut or move anything. This may seem a trivial point, but many field workers I have met who spend time in the forest are accustomed to moving about with a machete, slicing away vegetation where there is no trail. This most certainly cannot be allowed inside the plot, indeed, I have on some occasions recommended that a rule be instituted forbidding machetes inside the plot. Recall also that dead fallen trees will be counted on a single transect (see Chapter IX), and fallen logs on that portion of the plot should not be moved or otherwise altered.

C. Surveying the plot

At this stage, a plot location has been established and a base stake has been placed in the ground. I describe methods here for demarcating the plot by placing additional stakes at intervals of 20 meters on a rectangular grid. The survey requires placing a device which measures distance, direction, and inclination on a tripod at one stake, then measuring ahead 20 m in a precise direction to place the next stake. Distance and inclination must be measured precisely.

1. Surveying tools. I first wrote these methods in 1997, recommending use of a surveying compass for the measurements. The compass consists of a large horizontal compass face and needle, on top of which sits a telescopic sighting device which can be rotated horizontally to take a bearing and vertically to measure inclination (Forestry Supplier sells a Sokkia surveying compass and tripod, catalog #37485 and #37487). Today, as I write in 2008, laser rangefinders accomplish all three measurements: direction, inclination, and distance, meaning the tape measure is no longer needed. In all other respects, however, the methods with a surveying compass vs. a laser rangefinder are identical, and either will suffice. There are also much more sophisticated and expensive surveying devices known as 'total stations' which may be used if available.

The rangefinder I recommend is LacerAce 300 (MDL Lasersystems, http://www.mdl.co.uk/handheld_laser_systems/laserace-300/index.html). It must be mounted on a tripod, and the tripod should have a plumb bob hanging below to allow it to be positioned directly above a stake. A target should also be created: a flat piece of wood with white cardboard a large and brightly colored X affixed.

Two sighting poles are also necessary: approximately 2 m in height with tape measures attached at identical heights on each. One pole should have a leveling bubble or plumb bob so that it can be held precisely vertically. The target should be attached to the second pole in such a way that it can be easily moved up and down.

Rubber straps or ropes are also needed for pulling and tying vegetation out of sighting lines.

2. Grid markers at 20-m corners. The mapping grid is intended to be permanent, so that it can be relocated (at least for several years). In most circumstances, I recommend use of PVC tubes as markers: 1.2 m long by 50 mm in diameter, with a 1.5 mm wall thickness. If possible, I suggest pounding one PVC stake all the way into the ground, until its top is flush with the leaf litter. Then a metal tag should be wired to the top of the stake by drilling a small hole through the PVC. The stake number should be etched into the tag. This tag will allow the stake be located beneath litter or mud using a metal detector. This sunken stake make a long-lasting marker, and is also out of sight and out of the way. Of course, these permanent, sunken stakes should only be used with permission of the land owner.

During the census work, a temporary PVC stake should be inserted at each 20x20 m corner for high visibility; painting its type bright orange is useful. Two or three bright pieces of orange flagging, about 1-m long, should then be hung from tree branches around each stake. This makes the 20-m corners easy to find from a distance. The coordinates of the 20x20 m quadrat should be marked on the flagging and on the top of the stake (the coordinate system is described below). These marking flags and stakes will not last long. Forestry Suppliers sells various flexible, colored, plastic flagging material.

3. Grid markers at 5-m corners. These will be placed the day tree ennumeration begins. These are not intended to be permanent, though this depends on local preferences. Smaller PVC stakes, 1 m long with a 13 mm diameter and 1.5 mm wall, suffice, or even painted wood if they will not be left long. It is important that they be readily visible, and it is useful if they are distinguishable from the 20-m stakes.

4. Surveying a line. In describing the survey below, I refer to the measuring device as a rangefinder, though a surveying compass can be substituted. The stake from which a measurement is begun is called the origin, and the next stake, which is to be placed, is the target.

To survey a single line means placing a series of stakes at precisely 20-m intervals along a straight line. At least three, and possibly four people are needed. One person (Surveyor A) handles the rangefinder, setting it directly above a grid marker using the tripod and plumb bob and aiming it in the chosen compass direction. This direction is north for placement of the second stake and for subsequent stakes on the first line, but east, west, and south sightings will be necessary. Two assistants move vegetation aside to allow a sighting line from the surveying compass to a point exactly 20 m ahead. Saplings and lianas can be bent aside and tied in position with rubber straps or ropes. Vegetation must not be cut!

Surveyor A then measures the height above the ground of the rangefinder using one of the sighting poles. Surveyor B holds the other sighting pole vertical, with the target conspicuous, and moves around until a location 20 m due north is located. Surveyor A finds the pole with the laser. Then B indicates with his or her finger the height on the second pole that matches the height of the rangefinder. Shining a flashlight on the target (or finger) can help in dark forest. Surveyor A must locate the target with the laser, then note the distance and inclination (vertical angle).

If the inclination is non-zero, a distance correction is necessary, because the 20 m must refer to horizontal distance (Fig. V.1). The distance *d*, parallel to the ground, is longer than 20 m, and is found from the formula

$$d=\frac{20}{\cos\theta} \qquad \text{Eq. V.1}$$

where θ is the inclination. For example, if $\theta=8^{o}$, *d* is 20.2 m. See the appendix at the end of this Chapter V the distance corretion for half-degree increments from 0.5^{o} to the 30^{o}. A copy of this table is needed in the field. With the preliminary reading of θ, a corrected value for *d* is read from the table. Surveyor B moves the sighting pole back to precisely *d* meters, and surveryor A must relocate the pole (asking B to move to the side if necessary) and read again. If changed, a new *d* must be read from the table and the pole moved again and resighted. When the inclination no longer changes, B places a permanent marker at the spot directly below the target (using the level to make sure the pole is vertical).

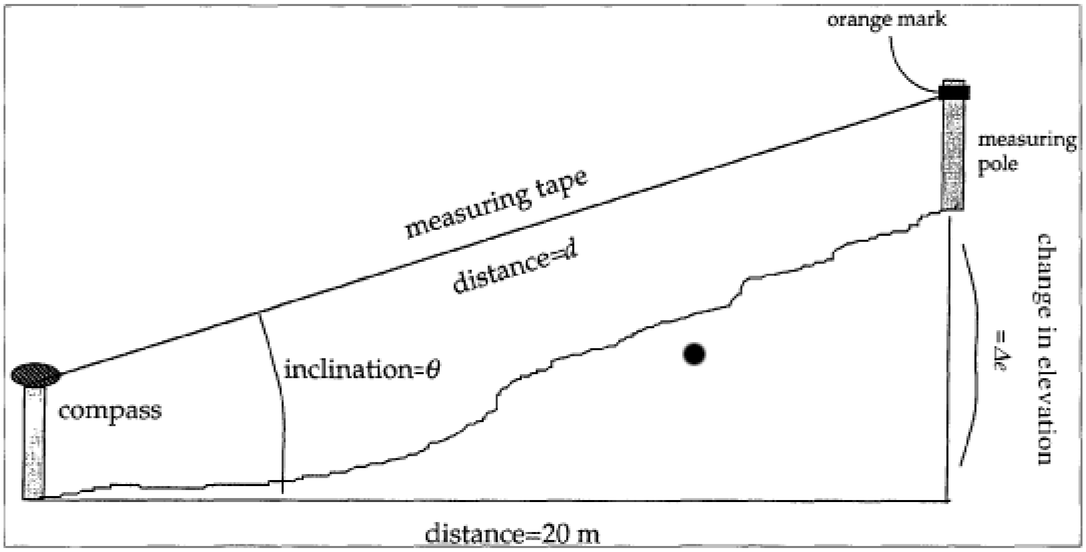

Figure V.1. Surveying on an incline. The distance measured is *d*, parallel to the ground, and must be > 20 m, as given in the Chapter V Appendix. If using a laser rangefinder, it sits where the compass is indicated, and no measuring tape is needed.

Surveyor A records the horizontal distance and the inclination to the final position exactly, plus the bearing (exactly north in most cases), and the numerical designation of the two stakes (the numbering system is described below). It is important to record the inclination as negative for downward slopes and positive for upward; this is easy to forget! Also, the stake numbers must be recorded in the correct order -- first the origin stake, where the rangefinder stood, and second the target, toward which it was aimed.

Now advance to what was the target stake and place the rangefinder there. In larger plots, where the survey line will be much longer than 100 meters, I recommend a back-check: aiming the rangefinder backwards to confirm the distance, inclination, and direction. But in a plot of just 100 meters in size, I do not believe this is necessary. During training, however, back-checking should be standard until the personnel are consistent with their results.

5. A parallel line. A second line should be started 20 meters from the first, and the two lines surveyed in parallel. This helps reduce error, as the distance between the two lines can be checked. Imagine instead surveying one line a long distance through forest, then returning to the start to place a second line parallel. Obviously, the two lines will drift, ending up either too close or too far apart. The goal is to avoid that drift using side-checks: sightings between the two parallel lines. In larger plots, I recommend three parallel lines for the initial axes.

To place the parallel line, return to the base stake after the first stake (20 m north) is placed and turn east; place another stake exactly 20 m to the east. Then move to the east stake and place a fourth stake north of it, completing a square of four stakes. Figure V.2 shows three parallel lines and four stakes per line; in Figure V.3, the four initial stakes are those numbered 0000, 0001, 0100, and 0101.

The first stake placed (0000) and the last stake placed (0101) should be exactly 20 m apart, but this has not been measured. Taking the measurement of direction, inclination and distance between those two stakes is what I call a side-check. It should confirm that the bearing between them is exactly east-west, and that they are 20 m apart when corrected for inclination (correcting with the table of cosines in the Appendix). If there are substantial errors, the surveyors should return to the other stakes and try for improvement.

During training, and for the very first stakes placed, side-checks should be done for every new pair of stakes. One the surveyors gain experience, they will learn how accurate they are and know how often side checks are necessary. The rule should be to strive for 5-cm precision in distance and 0.25^o in inclination, but this is probably the margin of what is possible with this kind of equipment. If all measurements stay within 10 cm and 0.5^o, this should be sufficient.

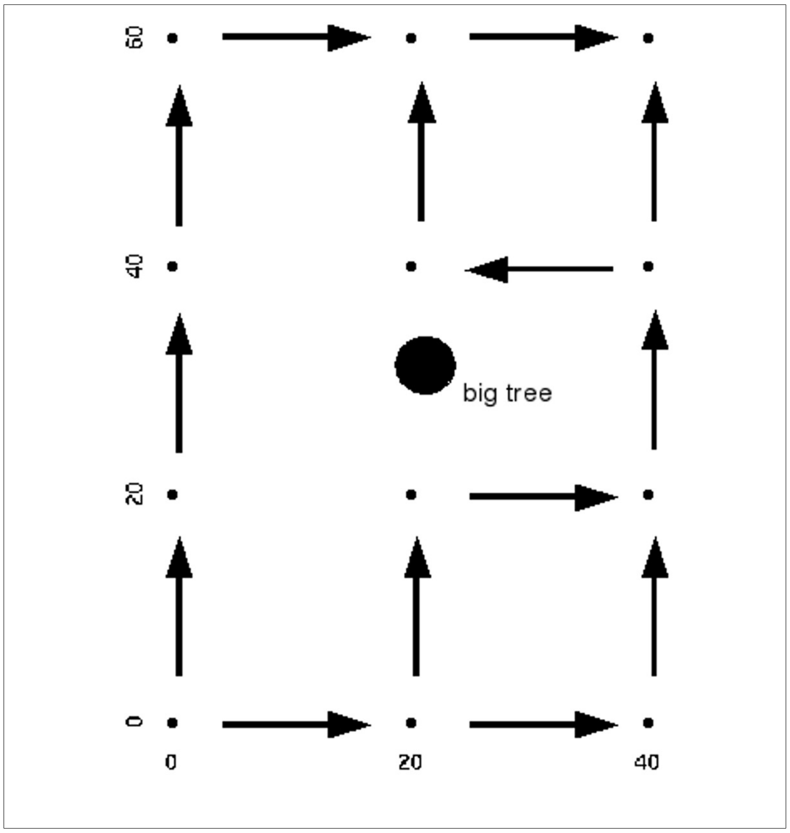

Figure V.2. Hypothetical survey of a section of six 20x20 m quadrats. Each arrow indicates a survey measurement, with the arrow indicating direction. The big tree had to be surveyed around.

In a plot only 100x100 meters, maintaining this accuracy should not be a problem. Once experienced, the surveyors should set eight stakes in two parallel lines (up to 60 meters from the original stake), then perform a side-check between the two lines. If they are within the accepted precision, finish the lines out to 100 meters, then do one more side-check between the ultimate pair. This means two side checks between each pair of lines.

Whenever a side-check is done, record the measurements! These can be used in creating the topographic map, and they produce a record on survey accuracy.

6. Subsequent lines. From then on, single additional lines are added, with two side-checks per line, until the plot is finished. That is, after the first two parallel lines, the third line of stakes is set from start to finish, using the second line for side-checks, etc (Fig. V.2).

7. Obstacles. Unfortunately, in a real forest, large trees block some sighting paths. When one of the northward lines is blocked, it will be necessary to place a new stake from one of the parallel lines. Likewise, side-sightings may be blocked, so it is never possible to do side-checks at every intended stake. As long as errors can be kept small enough that side-checks are only necessary at 40-60 m intervals, this is not a problem. There will inevitably be some stakes that cannot be sighted from any of the four adjacent stakes. Here, a sighting from a diagonal stake must be used, with the distance adjusted to 28.3 m. Intermediate sightings to the mid-point of a quadrat (14.14 m) might be necessary in this circumstance.

Another difficult circumstance is when the position of a new stake is occupied precisely by a tree. If the trunk has a diameter < 40 cm, I recommend putting the stake as close as possible to its real position; at this diameter, it will be within 20 cm of the correct position. For larger trees, the PVC stake should simply be attached to the trunk with a nail, and the flagging hung as always to make it visible. In either case, the stake should not be used as an origin of sightings to other stakes, as this would compound the error. If a large rock occupies a stake's position, paint can be used to mark the location.

Figure V.2 shows a fictional but plausible surveying record for a portion of the initial axes.

8. Additional surveying in dissected terrain. In large plots where these is substantial interest in knowing the topography precisely, additional surveying should be done in highly dissected terrain. For example, if there is a substantial mound, hole, or stream within a quadrat that would be missed by placing stakes only every 20 m, additional points can be surveyed at either 10- or 5-m intervals to capture the feature. Permanent stakes should be placed at these positions, but marked carefully to indicate their precise location (to prevent confusing them with the main 20-m stakes).

In the one-hectare plots described here, this additional surveying is probably unnecessary. Accurate tree mapping, as long as the 20-m quadrats are accurately marked. So additional surveying can be done according to the interests of local scientists.

9. Quadrats and subquadrats. The 20x20 m quadrats into which the plot is surveyed become the unit of field labor; their accuracy is the basis for any future mapping of trees or other features. To be precise about tree-mapping, however, a 20x20 m quadrat is too big in dense forest, and I recommend further subdivision into 5x5 m subquadrats. These markers, though, as less permanent, and can be placed immediately before tree ennumeration. Thus I postpone a description of methods for placing subquadrats to the next chapter.

10. Stake and quadrat numbering. The most convenient quadrat-numbering system for field work is to designate a quadrat by column and row, where rows are 20-m swaths numbered from south to north, and columns from west to east. Quadrat 0104 is column 01, row 04 (Fig. V.3). The initial row and column are 00, thus quadrat 0000 is in the southwest corner, and 0005 is in the west-most column, row 05. I always use numbers with four digits in recording quadrats.

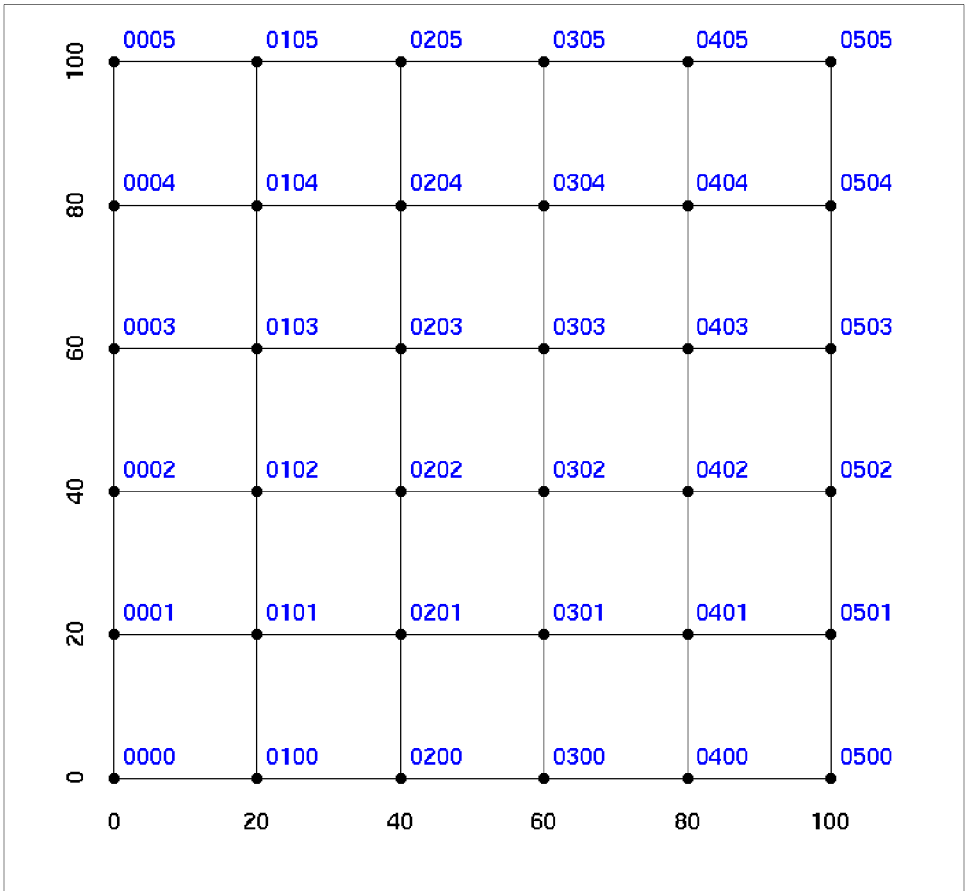

Figure V.3. Quadrat numbering. The leftmost (ordinarily west) column is 00, and the bottom row is 00. Quadrats are designated with column-row.

The stake at the southwest corner of a quadrat has the same number as the quadrat. Thus, the base stake of a plot (far southwestern) is 0000. The southwestern corner of quadrat 0104 is stake 0104. The northwest corner of the same quadrat is stake 0105 (Fig. V.3). These numbers are marked on the stakes and on flags above them, to allow navigating in the plot. To find any quadrat or a tree within, proceed first to the stake with the same number, then look into the quadrat to the northeast.

D. Remeasuring survey points

The final estimates of forest biomass and carbon rely on estimates of plot area: if the 100x100 meter plot is really 101x100.5 meters, then its area is not exactly one hectare, and this error propagates into estimates of carbon stocks. To gauge errors in measurements of plot size, and few randomly selected stakes should be surveyed, ideally by a different team of people than first did it and without knowledge of the first measurement. From each plot, I suggest repeating the distance and inclination measure for 3 pairs of stakes.

E. Time and labor for placing the grid

In plots where I have worked, teams of 3-4 people can place 7-10 stakes per day (see Manokaran et al., 1992). This means a one-hectare plot can be surveying in four days by a team of four people. This does not include the time needed to fill in the 5-m grid; this is usually done during tree enumeration.

Key issues for the topographic census

Accurate measurement of the plot and placement of stakes is crucial to every subsequent measurement requiring plot area

Stakes should be firmly placed and well-marked

Two parallel lines from the base stake start the survey

Regular side-checks ensure that two lines do not drift apart

Keep records on side-checks since they can be used to assess accuracy of the topo map

Appendix -- Ground distances *d* that give 20-meter or 10-meter horizontal distances (see Fig. V.1). The inclination θ is in degrees. For example, if the ground is inclined upward at 4.0°, the distance measured parallel to the ground should be 20.05 meters. The second column gives the correction for a 10-meter horizontal distance (always exactly half). For angles > 20°, a table of corrections can be created using Equation V.1.

θ	*d* (20 m)	*d* (10 m)
0.0	20.00	10.00
0.5	20.00	10.00
1.0	20.00	10.00
1.5	20.01	10.00
2.0	20.01	10.01
2.5	20.02	10.01
3.0	20.03	10.01
3.5	20.04	10.02
4.0	20.05	10.02
4.5	20.06	10.03
5.0	20.08	10.04
5.5	20.09	10.05
6.0	20.11	10.06
6.5	20.13	10.06
7.0	20.15	10.08
7.5	20.17	10.09
8.0	20.20	10.10
8.5	20.22	10.11
9.0	20.25	10.12
9.5	20.28	10.14
10.0	20.31	10.15

θ	*d* (20 m)	*d* (10 m)
10.5	20.34	10.17
11.0	20.37	10.19
11.5	20.41	10.20
12.0	20.45	10.22
12.5	20.49	10.24
13.0	20.53	10.26
13.5	20.57	10.28
14.0	20.61	10.31
14.5	20.66	10.33
15.0	20.71	10.35
15.5	20.75	10.38
16.0	20.81	10.40
16.5	20.86	10.43
17.0	20.91	10.46
17.5	20.97	10.49
18.0	21.03	10.51
18.5	21.09	10.54
19.0	21.15	10.58
19.5	21.22	10.61
20.0	21.28	10.64
20.5	21.35	10.68

Chapter VI. Measuring and mapping trees

This is the core of the work: the reason for establishing the plot. All trees above a set diameter limit, with all of their stems, must have their trunk diameter measured at a precise height. In the carbon inventory, the minimum diameter limit is 100 mm in most of the plot, but 10 mm in a small subsection. Measuring diameter is straightforward in the idyllic tree form, where the trunk is a straight cylinder; most of the details of the methods govern the non-idyllic tree: forked trunks, crooked or swollen trunks, buttresses, strangler figs, etc. Trees are numbered with tags, and their locations mapped relative to the plot stakes. Tagging and mapping is important, since errors will be noticed later when data are screened, and individual trees may need to be relocated and remeasured.

The methods that follow assume that a plot in forest vegetation has already been surveyed and gridded. Stakes are in the ground every 20 m, marked and numbered for easy navigation through the plot. The surveying does not need to be finished, though: the tree enumeration teams can start as soon as the initial quadrats are placed.

A. Equipment and Supplies

Each enumeration team needs three diameter tapes (for two measurers plus the supervisor), two 25-m tape measures, two hand-held compasses, a hammer, pencils, two clipboards (for the two people recording data), and a small paint brush and paint. I recommend 1.6-m cloth diameter tape from Forestry Supplier (Forestry Suppliers Metric Fabric Diameter Tape, model 59571); one longer tape may also be needed for very big trees (model 59576). One of the enumeration teams also needs three tenth-millimeter accuracy metal dial calipers; these are only needed in a small portion of the plot, where small trees are measured (Forestry Supplier model 59911, for example; be sure it is metric). Other items are routinely available. Waterproof paper is useful for work in the rain forest, but not essential. If waterproof paper is not used, plastic sheets are necessary to protect the paper from rain. Each measurer also needs a straight pole exactly 1.3 m long, with flat ends, easily made from small trees near (not in!) the plot.

A large set of calipers may be needed for measuring the diameter of large trees in cases where a tape cannot be wrapped around the trunk. Large calipers are also useful for measuring the size of fallen logs (Chapter IX).

The enumeration teams must also place the grid markers at 5-m intervals, and thus need 21 stakes for each 20x20 m quadrat along with ropes and tape measures for positioning them (as described in the previous chapter). One 40-m piece of light rope is necessary for demarcating each subquadrat.

Aluminum tags are used for marking trees. National Band and Tag Co. (Newport, Kentucky, USA) has 44x16x1.3 mm tags with rounded corners and numbers already engraved (see http://www.nationalband.com/ for many different options). A less expensive alternative is to purchase sheets of thin aluminum tags that are soft enough to have numbers etched on with a nail. This latter approach should be used for replacement tags (when one tag number is lost) and tags for multiple stems.

I recommend tying tags to trees < 150 mm dbh with tough nylon or polyethylene thread. Aluminum nails, 100 mm long, can be used for attaching tags to larger trees. Waterproof paint that will last in wet forest is needed for marking trunks. Most oil-based exterior house paints or highway paints probably suffice. Each field team needs a paint can and brush.

An aluminum ladder extensible to 5 m is necessary for measuring large, buttressed trees, and also for collecting wood cores well up some tree trunks (Chapter VIII). Only one ladder is needed, and it is only brought to the forest on one day. In some parts of the world, good tree climbers can be found, possibly obviating the need for a ladder.

B. Plants to Include

The purpose of a biomass and carbon inventory is to estimate how much wood is present in a forest, and this requires measuring all woody stems. In a tropical forest, this includes lianas, palms, strangler figs, and bamboo, not to mention trees with gigantic spreading buttresses. The need to include all simplifies the rule: if it is a woody stem larger than the minimum diameter limit at 1.3 m from the rooting point, it is included. The only stems that might be excluded are some herbaceous species with pseudo-woody stems (Marantaceae, Araceae, Cyclanthaceae). Some species in these families have soft green stems larger than 10 mm, but they are not included in the census.

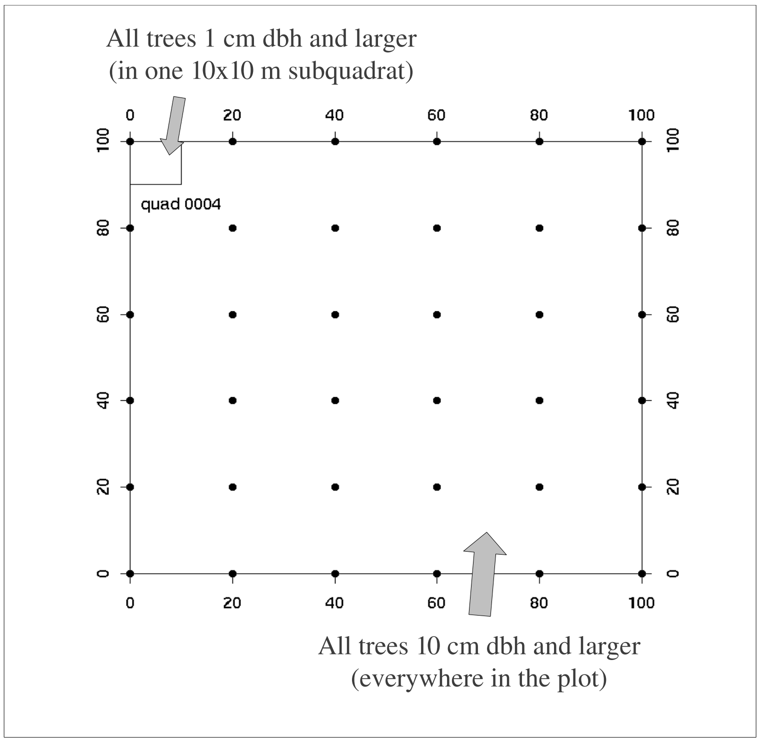

Fig. VI.1. Location of the 10x10 section where smaller trees are mapped.

The minimum diameter is 100 mm in most of the plot, but a subsection will include stems larger than 10 mm diameter (Fig. VI.1). The height of measure, 1.3 m, is traditionally called 'breast height', but for clarity, I will avoid that phrase. Instead, I will use the acronym HOM, meaning the height-of-measure, as this is key in describing the rules for choosing where to measure a tree.

C. Demarcating subquadrats

Tree enumeration teams are responsible for filling in the 5-m grid markers, best done at the start of work in each 20x20 m quadrat. The 5-m points can be located with rope and tape measures alone. First, with tape measure, locate the mid-point of all four sides of the quadrat and mark it with a stake. Note that the mid-point may not be 10-m from the ends, if the quadrat is inclined: if the two edge stakes are 21 m apart, the mid-point is at 10.5 m. Next, run two ropes straight across the diagonals of the quadrat, and place a stake directly below the intersection. (As long as the ropes are straight, this correctly locates the middle even if sloped.) This divides the 20x20 quadrat into four of 10x10. The identical procedure can be repeated to locate 5-m stakes.

Placing a stake every 5 m greatly facilitates the enumeration, making it less likely to miss trees and easier to map their locations. It is time-consuming, though, and the alternative of placing stakes only every 10 m is reasonable. In what follows, I assume stakes every 5 m, but there are no great differences if stakes are placed every 10 m.

I recommend placing ropes around the four edges of the 20x20 to show the boundaries clearly. This helps especially where two different teams are working at the same time in adjacent quadrats.

D. Work sequence

The 20x20 m quadrat, as marked during the survey, is the unit of work. Each mapping team works a single quadrat until it is finished. If there are two or three enumeration teams, I suggest each work a single column of quadrats, starting with column 00 (Fig. V.3). Thus, if there are three teams, they start in columns 00, 01, and 02, and the first to finish one column begins in 03. Work begins at the base of each column and follows the quadrat numbering (Fig. V.3). In a plot laid on a north-south axis, work proceeds northward up each column, and eastward from column to column.

Within each quadrat, I recommend that teams follow the consistent sequence in working through the subquadrats of 5x5 meters. Subquadrats are numbered as in Fig. VI.2, one entire 5x5 should always be completed before moving to the next. Solid arrows indicate a suggested work sequence from subquadrat to subquadrat, and open arrows a sequence within a subquadrat. Regardless of the order selected, following a consistent path is useful because the tag sequence is then predictable, and this makes later attempts to find a particular tree easier. Moreover, it helps assure that every stem is located.

E. Dead wood

The carbon inventory includes a transect to count and measure dead and fallen wood. It is important the main census team be aware of the location of this transect, down the center of column 00 (quadrats 0000 to 0004; Fig. V.3). They must avoid disturbing fallen wood in those quadrats. Check Chapter X for details.

F. Data Collection

1. Data sheets. Data from each 20x20 m quadrat go onto two data forms: the main datasheet plus a map. Each include spaces at the top for recording the plot number, quadrat number, names of the field crew, and dates. Sample datasheets are provided at the end of this chapter. When data from one quadrat do not fill a sheet, data from a second quadrat should never be added: one sheet should only have data from a single quadrat. On the other hand, when a quadrat is not finished at the end of one day, data from the same quadrat on the next day <u>should</u> go on the same sheets.

2. Mapping trees. Once a 5-m grid is marked, mapping the location of each tree is fairly easy, indeed, mapping to a precision of 5 m is already accomplished. Trees are mapped entirely by eye by marking a spot on the field map. In quadrats where trees ≥ 100 mm dbh are included, a map of one full 20x20 m quadrat should be used. But where trees ≥ 10 mm are included, a map of a 10x10 m section is recommendable. Both kinds of maps are provided at the end of the chapter.

Trees are mapped where they are rooted, so leaning or prostrate trunks require care: the crown and most of the trunk may not be in the rooting subquadrat. If a prostrate tree has roots along a substantial length of the trunk, then the trunk base is mapped. Large trunks should be indicated with large circles, the center determining the tree's location.

Each tree's tag number is recorded next to its spot on the map. If tag numbers have more than four digits, and the initial digits do not change within a quadrat, then I suggest writing only the final four digits on the map, with full tag number of the first tag of the quadrat entered at the top of the map.

No coordinates are entered in the field. Rather, coordinates are captured later by digitizing the maps.

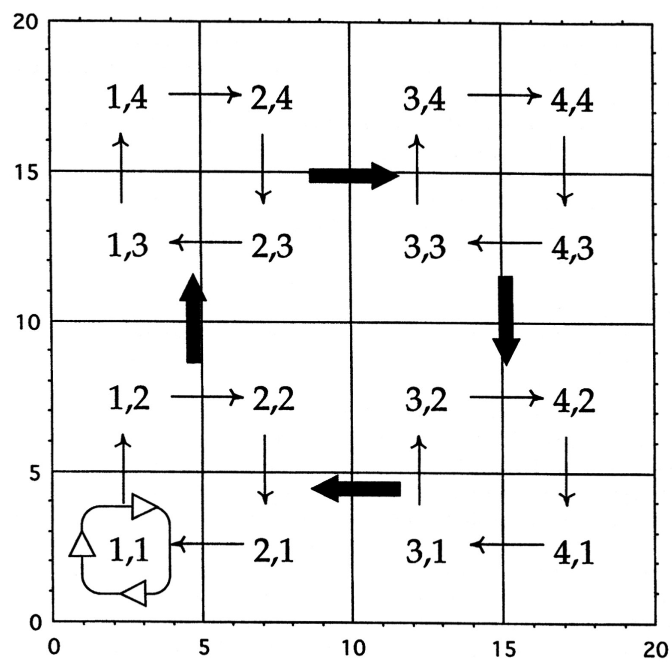

Fig. VI.2. Recommended work sequence and subquadrat numbering within a 20x20 m quadrat. Each small square is 5x5 m. Black arrows indicate a work sequence between subquadrats; open arrows within a single subquadrat.

3. Tagging trees. Tags are simply attached with loops of string around smaller trunks. Loops must be large enough to allow for growth: 600 mm for stems < 60 mm diameter, 1 m for trees < 150 mm diameter. Larger trees (≥ 150 mm) are tagged with nails, with at least 50-60 mm of nail left above the bark. Nails should not be placed at the HOM (height of measure), where the diameter is taken.

Tags should be placed in a numerical sequence that matches the work sequence: clockwise within quadrats, northward up columns, etc. If several teams work at once, a sequence of numbers must be assigned to each column. Tag sequences should be prepared before going in the field, strung on a coat hanger or similar wire. A sufficient number of 600-mm pieces of thread should be precut and carried so that single pieces can be easily pulled out. About 30 1-m pieces should also be cut for every quadrat (for trees 60-150 mm diameter).

See the section below on tagging of multiple stems.

4. Trees to include. Within the entire 1-ha plot, all trees with a diameter ≥ 100 mm are mapped, tagged, and measured. This refers to the diameter taken following the rules below.

In a single 10x10 m section of the plot, all trees with diameter ≥ 10 mm should be censused following the same methods. This should be the northeast 10-m section of the 1-ha plot, within quadrat number 0004 (Fig. V.3, Fig. VI.2).

5. Measuring trees. Here is the largest and most complicated section of all the methods. Good measures of stem diameter are critical, since diameter is the basis of estimating both height and biomass. Recording the diameter is straightforward on regular, cylindrical stems: calipers are used for trees < 60 mm diameter, and a diameter tape for larger trees. In either case, the diameter must be measured exactly perpendicular to the trunk. Breast-height is found with a pole exactly 1.3 m in length, which is placed against the tree. Diameter should be recorded to 0.1 mm accuracy.

Unfortunately, stems are seldom perfect cylinders, and quite a variety of difficulties in measuring arise. Following are 10 rules of tree measurement designed to ensure replicability of the measurements.

Rule 1. When using calipers, take the largest diameter. Most stems are in fact not circular in cross section, and calipers will record different diameters, depending on their orientation. With a diameter tape, this problem vanishes, but stems < 60 mm diameter cannot be measured accurately with tapes. Finding the largest diameter is easily accomplished by rotating the calipers while they are clamped lightly on the trunk. (This practices elevates the diameter of small trunks, and it the amount of the bias should be evaluated carefully.)

Rule 2. The HOM is always calculated 1.3 m above the ground on the uphill side. An HOM on the downhill side would be lower.

Rule 3. Breast-height is taken along the lower side of a leaning tree, not the upper (Fig. VI.3).

Rule 4. The HOM includes all stem above the ground, no matter the angle. Thus, a leaning stem may be measured only a few centimeters above the ground (Fig. VI.3), and on a sharply curved stem, 1.3 m must be measured around the curves with a tape measure. But in cases where a leaning stem has multiple rooting points so its origin is not clear, it should be treated specially, like a prostrate stem (rule 8).

Rule 5. Lianas, stranglers, and epiphyte roots should be pulled away from the tree trunk and the diameter tape slid underneath whenever possible. When the epiphytes cannot be moved, large calipers may be necessary. Any tree requiring large calipers should be marked as a big tree, to be measured later by the big-tree team (see Rule 7).

The remaining five rules govern situations where something prevents measurement at the standard height of 1.3 m, usually an irregularity in the stem. In these situations, the diameter must be taken at a different height.

For all cases where the HOM is not 1.3 m (rules 6-10), it should be marked with paint so it can be precisely re-located. In all cases, the height from the ground where the measurement was taken should be recorded (see data sheets at the end of the chapter).

Rule 6. When an otherwise cylindrical stem has an obvious swelling or constriction at 1.3 m (Fig. VI.4, case 2), the diameter is taken 20 mm below the lowest point of the irregularity. A thumb's width is used as an estimate of 20 mm. The trunk should be painted where it is measured.

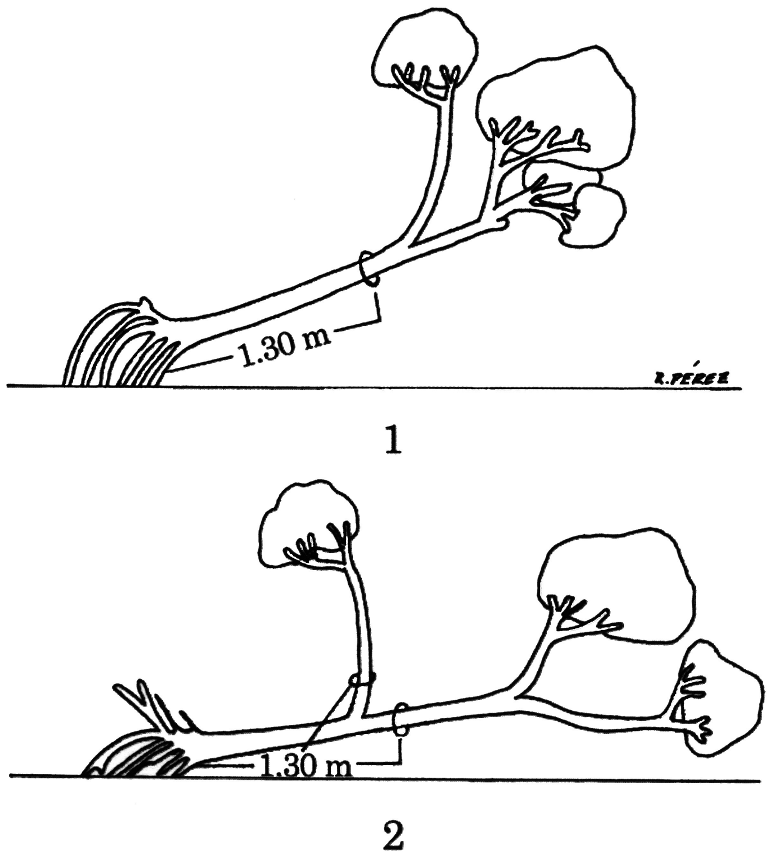

Fig. VI.3. Measuring multiple and leaning stems. Each stems is measured 1.3 m from the rooting point, measured along the underside of the stem. Case 5 illustrated how a leaning or prostrate stem is still measured at 1.3 m along the stem.

Rule 7. For trees with buttresses or stilts (Fig. VI.5), the diameter must be measured at least 80 cm above the top end of the highest buttress (or stilt). If 1.3 m is sufficiently high, then the measurement is made as usual. But often it will be necessary to measure further up the trunk, and in some very large trees, a ladder will be needed. The HOM should always be painted. In most cases, I recommend these trees be marked as 'problems', then all can be measured on the final day by a team of 3-4 people carrying the ladder throughout the plot (but in a one-hectare plot, there should seldom be more than one such big tree).

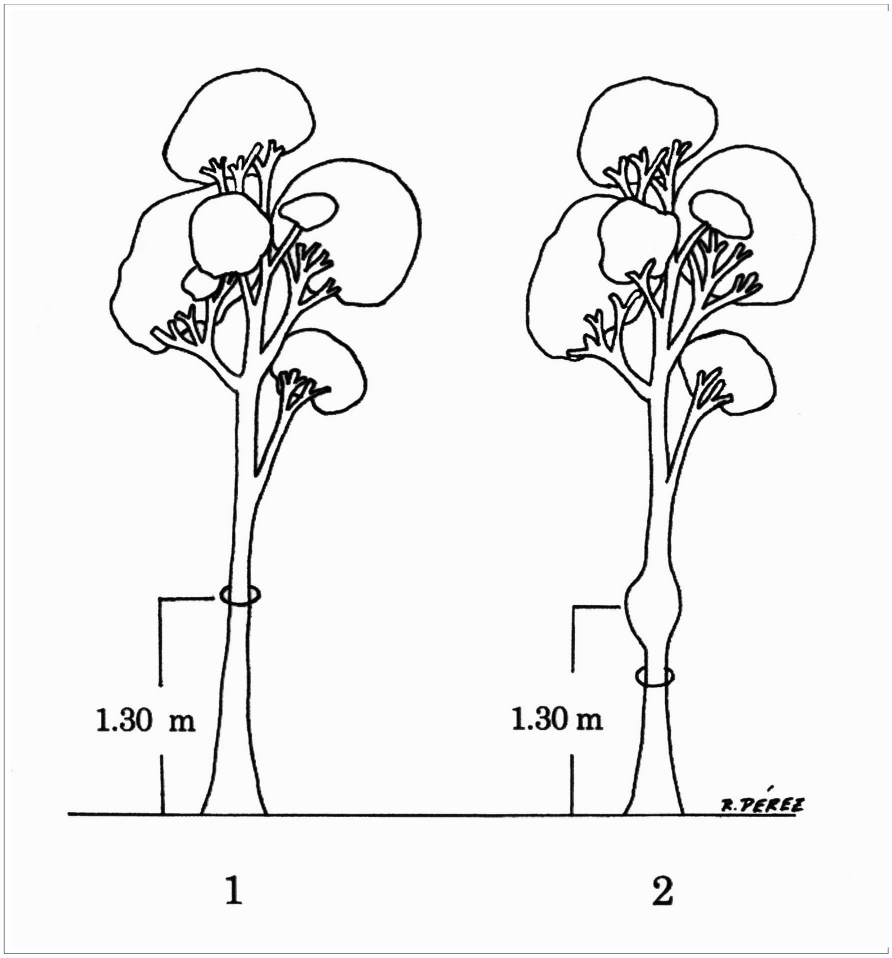

Fig. VI.4. Case 1, the standard measurement at 1.3 m. Case 2, the trunk is swollen at 1.3 m, so the measurement is taken lower. The trunk is painted at the HOM.

There are giant trees whose buttresses are so high that even a 5 or 7 m ladder is insufficient to reach above them. I have employed tree climbers with ropes and harnesses for a few trees in the Barro Colorado plot in Panama (all kapok trees, *Ceiba pentandra*). A crude alternative is to have one person climb to the top of a ladder and hold a 2-m measuring pole marked clearly in 0.1-m gradations. A second person can stand several meters from the tree and read an approximate trunk diameter (above the buttresses) off the pole; binoculars may make this easier. Although approximate, it is better than no measurement at all, and since these trees are so rare, it will not have much impact on final biomass estimates.

Rule 8. Prostrate stems should always be paint-marked, since it is often not clear where 1.3 m along the trunk is. In general, they can be treated like leaning stems, with the diameter taken 1.3 m along the stem from its origin (rule 4), but multiple-rooting points and buried trunks can cause confusion. If so, a point above the ground should be selected and painted.

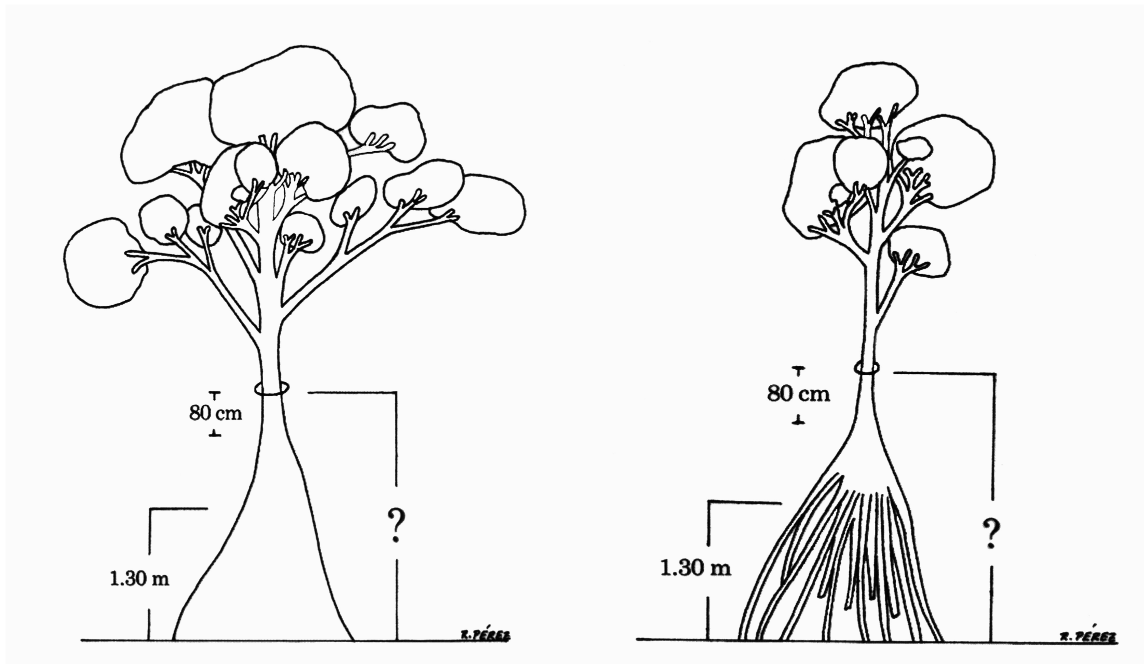

Fig. VI.5. Trees with buttresses or stilts are always measured at least 80 cm above the point where the stem becomes approximately cylindrical.

Rule 9. When a trunk is extremely irregular at all heights, an HOM must be chosen as best as possible, then painted and recorded so the tree can be re-measured at the same spot in the future. For example, there are species with highly fluted trunks, and nothing can be done except to wrap the tape around the flutings. Also, there are species whose trunks taper sharply at all heights, and there is nothing to do but measure at the standard 1.3 m. A code indicating that the trunk was irregular at the HOM should be recorded so that future workers know.

Rule 10. This is for trees where no rule works: there is no rule 10. There will inevitably be some trunks that simply defy measure, for instance when completely buried in a strangler fig. The best possible measurement must be taken -- at least some estimate is better than none -- and the location of the HOM painted and recorded. As long as these cases are rare, the best estimate of the team leader is acceptable. However, if there is a consistent problem unforeseen by rules 1-9, then a new technique must be developed and applied regularly.

6. Multiple-stemmed individuals. I have left aside, so far, cases where a single plant branches or forks below 1.3 m, or has more than one stem connected underground. This situation requires special rules for mapping, tagging, and measuring (Fig.VI.6).

Separate stems which are obviously connected to one another below 1.3 m, either above or below the ground, are considered part of the same individual. A single tag should be tied or nailed to the largest stem of the group. In addition, all stems, as defined below, should be given a separate type of tag following the same protocol for tagging as used on main stems (section 3 above). For example, in trees with two stems, the main trunk is given a primary tree tag (section 3), then each stem gets a stem tag, numbered 1 and 2; and so on for more stems. Stem tag 1 should always be the largest diameter stem (if several stems have the same diameter, then the tallest should be tag 1). Stem tags are typically not numbered in advance, but at the moment when they are applied (using thin aluminum tags with nails to etch numbers).

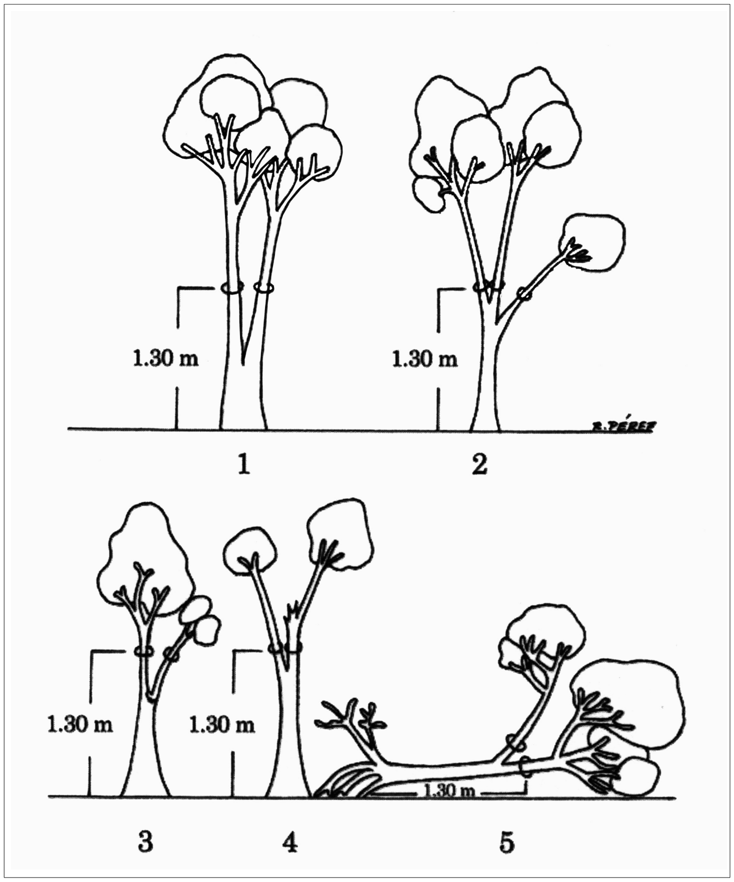

Fig. VI.6. Measuring multiple stems. Each stems is measured 1.3 m from the rooting point, measured along the stem. Case 5 shows how a stem out of a horizontal trunk is measured.

The full extent of a plant's cluster is drawn on the map (but later, only the center point of the cluster will be digitized). Each stem ≥ the minimum diameter cutoff is measured following the rules described above, and every one of the diameters is recorded on the main datasheet (Appendix 1 at the end of Chapter). If one stem is irregular or buttressed, its HOM may not be at breast height, but all other stems would still be measured at 1.3 m.

Any branch below 1.3 m is considered a second stem, even if it is horizontal, as long as it is above the minimum diameter cutoff at 1.3 m from the rooting point. The HOM is found by measuring from the ground, following any forks (Fig. VI.6). A branch above 1.3 m is not considered a stem. If there are extra stems but they are below the minimum diameter, the tree is not considered multiple.

Prostrate stems can have many vertical sprouts (Fig. VI.6, case 5). If the sprout is > 1.3 m from the rooting point, then it should not be considered a stem, following the rule that the HOM is measured along the stem. There are rare cases where prostrate stems grow more roots, and so have multiple rooting points. In this circumstance, I suggest measuring all sprouts within 1.3 m of any rooting point, and measuring the main (prostrate) stem 1.3 m from what appears to be its original rooting point.

In some cases, it is not clear whether adjacent stems are connected underground. For species that do not normally grow as clones, a connection must be reasonably obvious to count two stems as one individual.

Multiple stems can create odd circumstances which create confusion. One case that is fairly common is where a trunk forks just below 1.3 m, and the fork causes a swelling. Rule 6 calls for this tree to be measured below the swelling, but this would require measuring below the stem fork, where there is only one trunk. Instead, the standard should be to measure the two stems above the fork, where they are regular, so that the tree is recorded with multiple stems. Another confusing case is where a buttressed tree requires a high HOM, for instance 3 m above the ground, and also has a trunk fork below 3 m. Because the fork is above 1.3 m, it should not be measured as a multiple stem, even though the main stem is measured higher. In all such cases, as for any unusual HOM, stems should be painted where measured.

7. Palms. Most palms can be measured following the standard rules. A couple confusing features arise, though, special to palms. First some can be shorter than 1.3 m tall but have stems ≥ 10 mm diameter; this circumstance is rare in non-palms. Regardless, these are not included in the census. The following concerns only arise when a palm is approximately 1.3 m tall and has a large enough diameter stem to include. The top of the stem must be located exactly: it is defined as the base of the lowest living leaf sheath. A difficulty arises when dead leaf sheathes persist, hiding the base of the lowest living sheath, and then the location of the top of the stem can only be estimated. When measuring the diameter, dead sheathes are not removed, but are pressed as tightly as possible against the stem. Leaf petioles do not count as part of a stem even when they resemble a stem. Thus palms are often excluded even though their leaves are much taller than 1.3 m, and likewise for tree ferns.

8. Lianas. For carbon and biomass inventories, climbers often grow enough wood to justify their inclusion. Broadly, the sampling method matches that for trees: each stem should be tagged and measured 1.3 m from where it roots in the ground. What makes lianas unusual is that stems can cover great horizontal distances and also branch frequently, but these two characteristics do not require different methods. Rooting points must be located, and diameters measured following rules 1-6 above.

Most unusual with lianas is the tendency for stems to re-root far from their initial rooting point. In many cases, a single stem may rise high in the canopy then descend and root elsewhere, so it will not be evident that two different rooting spots belong to the same individual. The rule must be to measure 1.3 m from all rooting locations, and to record these as two separate individuals, mapped at separate locations. A comment should be added that two roots belong to the same individual where this is detected.

9. Stranglers. Stranglers are measured whenever they have a trunk above the minimum diameter at 1.3 m, whether it adheres to a living host or the host tree is dead and gone. Trunks are convoluted, and sometimes several trunks near the ground merge further up, so the HOM of stranglers is problematic (and thus should always be painted). In some cases, a single trunk is measured well above the merging point, as if they were stilts, but if there is no clear, single trunk at any height, separate trunks are measured at 1.3 m as if they were multiple stems.

10. Dead trees. Dead wood is relevant to carbon inventories, and standing dead stems should mapped and measured just like live trees. Standing dead trees should have their stem diameter measured following the rules used for living trees. It is crucial, of course, to record on data sheets which trees are dead.

The census of standing dead and fallen dead (Chapter X) must include all dead wood above the minimum diameter. Confusion can arise where trunks fall but are held above the ground by branches or other trees. I suggest the rule that a trunk is counted as fallen if it touches the ground somewhere other than the rooting point. If it does not touch the ground at a second point, it gets counted with standing dead. Notice that this means a dead trunk could be horizontal but held aloft by other vegetation and it is counted with 'standing' dead. Most important is that the field teams working on fallen wood transects (Chapter X) and those measuring standing trees are communicating, and know that no dead wood is skipped over or counted twice.

11. Other data. Other than the diameter and information about the HOM, a few other pieces of information are important to record. Most important for a carbon inventory is to note if the trunk or crown of a tree is severely broken or damaged above 1.3 m. Stems leaning by more than 45^o or prostrate should be indicated. Also, stems which show signs of an old break below breast height should be noted; this information will be useful during a later census. Each of these pieces of information with a single-letter code, to simplify recording and later data entry (Table VI.1). The sample data sheet at the end of the chapter includes a column for codes. Additional codes can be devised for additional topics that are relevant at a particular site. If one tree has multiple codes, they should be separated by semi-colons on the data form. There is no reason codes have to be single characters; this is just for brevity and convenience. Every enumeration team should have a copy of the codes table with them during the work.

Table VI.1. Codes for describing several important and routine circumstances regarding a stem or its measurement.

code	description
L	Stem leaning by more than 45^o
P	Stem prostrate
Q	Stem broken above 1.3 m
I	Stem irregular where measured
B	Large buttresses
R	Signs that there was an old break below 1.3 m

The main data form also has a comments field where additional notes can be made. Comments are not going to be entered in the database, however, and their only purpose is to help field workers and supervisors finish accurate measurements (see next section on problems). Information to be recorded and stored about individual trees should all be done through codes.

12. Problems. Any plant that requires future attention should be marked as a problem with a letter 'P' in the final colum of the data form (see sample data forms after the Chapter). In addition, a brief comment can be recorded in the comments field to explain the question. Problems include those situations where the rules seem not to apply and which prompt the supervisors to consult with each other or the chief scientists before deciding what to do. They also refer to simple things, such as lost tags, which cannot be corrected until the next day, and cases where a big tree requires a ladder or perhaps other equipment to measure.

When the problem is resolved, the entries should be checked off on both sheets to indicate clearly that no further attention is required. By marking all problems in one column on the data form, supervisors can quickly screen for them. Once a problem is resolved, the problem code can be erased;

the comments should be left on the form, but marked to indicate the question was resolved.

G. Checking the Work

An advantage of working in teams, with field supervisors recording data, is that all work can be checked immediately. While recording data, each supervisor should also be monitoring the measurers and mappers. Occasionally, especially in difficult cases, the supervisor should remeasure the diameter to check accuracy. This is especially important early in the census, when measurers are inexperienced.

In addition, each of the team members should be encouraged to check each other's work. Both the person drawing the map and the one tying the tags can look for trees and check whether any have been missed. Anyone in the group might also notice that a diameter called out seems way off, prompting a remeasure.

Finally, after returning to the field office at the end of each day, supervisors should double-check the datasheets for the current day. Are all sheets present? Does every record have a complete set of legible data? Are there duplicate tag numbers? Problem should be reviewed and problems resolved immediately, when possible.

If the quadrat was not finished, the datasheets are set aside, to be used the next day. If the quadrat was completed, the full set should be placed in a manila folder, with one manila folder per quadrat. Problem sheets, though, should be kept in a separate problem folder until they are fully resolved. The folders should be kept in a file cabinet at the field camp until the taxonomy teams need them.

H. Remeasurement

A different and very important way to check data accuracy is to perform a systematic remeasurement of randomly selected trees. After several plots are finished, quadrats are selected at random from within the completed plots, and field teams return and remeasure all trees in those quadrats without the benefit of knowing what the first measurement was. The team remeasuring should not be the same as the team which first measured, and no team should know in advance which quadrats will be remeasured, nor when (it is a 'double-blind' experiment). The simplest approach for choosing remeasurement quadrats is to draw a single quadrat at random in each plot just after the tree measurements are finished.

Since trees are paint-marked when measured at unusual heights, the team doing remeasurements always knows the HOM used by the first team. This is unfortunate, since it removes one source of discrepancy: ideally, the second team would choose their own HOM. As a work-around, I propose that a different procedure be used for remeasurement in half of the plots. In these, a supervisor will spend one morning walking the forest just <u>outside</u> the plot, maintaining a distance of about 10 m from the plot boundary. He or she should choose 25 trees of all sizes, deliberately choosing some with irregular stems or otherwise requiring unusual HOMs: about half of the trees selected should be 'normal' while half have unusual measurement issues. The supervisor should mark each tree with flagging and put a number on the flag. Later, two different field teams must visit these trees and take diameter measurements <u>without</u> placing any paint mark. The two teams must works separately, not watching each other, and of course must record the flag's number so their measurements can be compared later.

There are two ways this quantitative revision should be used. First, it can be done at the very start of a census to determine whether improvements are necessary. One gauge of accuracy would be to compare with results at Barro Colorado (Condit 1998), where the mean deviation for plants < 100 mm dbh was 4.2%, and for plants ≥ 100 mm, 0.27%: the goal should be < 5% error in saplings and < 1% error in larger trees. If an estimate of accuracy early in the census suggests that these levels are not being reached, then the mappers should revise their techniques.

The error-check procedures should then be repeated during the second half of the project when most work is complete, simply as a record of accuracy. At this stage, the census-workers are experienced and have presumably reached a plateau of accuracy; it is too late to correct their techniques, anyway. Regardless, all measurements are recorded on data forms, just like the first time measurements were. At the sites where off-plot trees are measured twice, the forms must be clearly marked to indicate this.

I. Time and labor for placing the grid

A general average for progress in tree enumeration is 50-80 trees per day per person in a field team (Condit 1998), but this does not include the time needed to place 5-m stakes. The 1-ha plot described above will have 450-650 trees ≥ 100 mm diameter plus 50-80 ≥ 10 mm in typical tropical forests of the world (Condit *et al*. 1996). Two teams of four field workers (not including the supervisors) will thus require about three days to finish a plot. Assume the 5-m stakes adds a day of work, and another day for checking problems, measuring big trees, and the remeasurements, and I think five days is a reasonable estimate for finishing the tree enumeration.

J. Summary

By way of a summary of all the data collected by the mapping teams, I present data forms and review what is entered on each (Appendices 1-3 at the end of this Chapter).

The main datasheet is where most other information about each individual is recorded (Appendix 1). As for all sheets, the quadrat number, the first date and last date on which a quadrat is censused, and the field teams' names are recorded at the top. The supervisor should enter his or her name after checking the data form. For each plant, there are blanks for the following information: subquadrat number, tag number, stem tag, status, diameter, height-of-measure (HOM), codes, comments, and problems.

The subquadrat follows the numbering system in Fig VI.__.

Tag number is the complete tag placed on the tree; when a tree has multiple stems, this tag number must be reentered for each stem, and stem tag numbers are included. For most trees, with only a single trunk, stem tag is left blank.

The tree's status has three possible entries: T, L, or D, meaning tree, liana, or dead. It is important to always put something here.

A size in millimeters, with a single decimal point (ie, 0.1 mm precision) is entered in the diameter column. The associated HOM is entered <u>only if not</u> the usual 1.3 m. The height in meters at which the measurement was taken should be measured accurately, with 0.1 m accuracy.

After diameter and HOM come the codes, where a variety of information about a tree's status can be recorded. At the minimum, codes should be used for the situations described in Table VI.1. But the codes column can also be used to indicate other features of a tree, depending on what is considered important at a site.

The comments column should primarily be used to describe problems or questions. Cases which require a supervisor's attention should also include a 'P' in the problem field, to make it easy to review sheets for these cases.

The map sheet has -- for most quadrats -- the entire 20x20 m, with lines drawn at 5-m intervals to match the locations of the grid of 5-m stakes. Each tree is marked on the map relative to the stakes (lines) as closely as possible; very large trees should be indicated by larger circles (this makes it easier to relocate). The tree's tag number needs to be entered next to the mark on the map.

In the 10x10 m section where smaller trees are included (see Fig. VI.2), a finer-scale map of the

10x10 m should be used (Appendix 3). The four subquadrats it includes must be marked at the top. Thus, quadrat 0004 will have two maps, one for the entire 20x20 and a second for smaller trees in the 10x10 m subsection. The 20x20 m map in this case should be blank in the top left portion (ie, do not enter the larger trees twice).

Key issues for the tree census

Diameter is easy to measure as long as trunks are straight and regular in shape

Irregular stems require consistent methods about locating the HOM -- height-of-measure

Special rules for handling leaning, prostrate, multiple, or irregular stems need to be carefully spelled out and should be followed consistently (so two people measuring the same tree get the same diameter)

Buttressed trunks should always be measured 80 cm above the top buttress

HOMs at unusual heights should be indicated with paint, with the height recorded

In a carbon inventory, standing dead trees are also measured

Palms, tree-ferns, stranglers, and lianas are included and often require special rules

Random, double-blind remeasurements of a portion of trees should be included

Appendices -- Data forms for main tree census

The next three pages provide sample forms for recording the tree enumeration data: measuring and mapping.

1. The first form is where stem measurements are recorded.

2. Next is a full quadrat map, to be used where trees ≥ 100 mm diameter are included.

3. The final sheet is a finer scale map, showing just a 10x10 m portion of one quadrat, to be used where trees ≥ 10 mm are included. In the latter case, both the quadrat number and the four subquadrat numbers must be indicated.

Main tree inventory

Plot: ______ **Quadrat:** _______ **Start date:** _____________ **End date:** _____________

Field crew: ____

Supervisor: _________________________ Data Entered by: _________________ Date: _________

GPS coordinates of 4 corners: __________ ___________, __________ ___________,

__________ ___________, __________ ___________

sub-quad	tag	stem tag[1]	status T/D/L[2]	diam (mm)	HOM[3] (m)	codes	comments	prob
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1 Leave stem tag blank when there are no multiple stems
2 Tree, Liana, or Dead
3 Leave HOM blank when it is the standard 1.3 m

__,__ ____________ ____ _______ ________ _____ _________ ______________________________ ____

Main tree inventory: quadrat map

Plot: ______ **Quadrat:** _______ **Start date:** _____________ **End date:** _____________

Field crew: ____

Supervisor: _________________________ Data Entered by: _________________ Date: _________

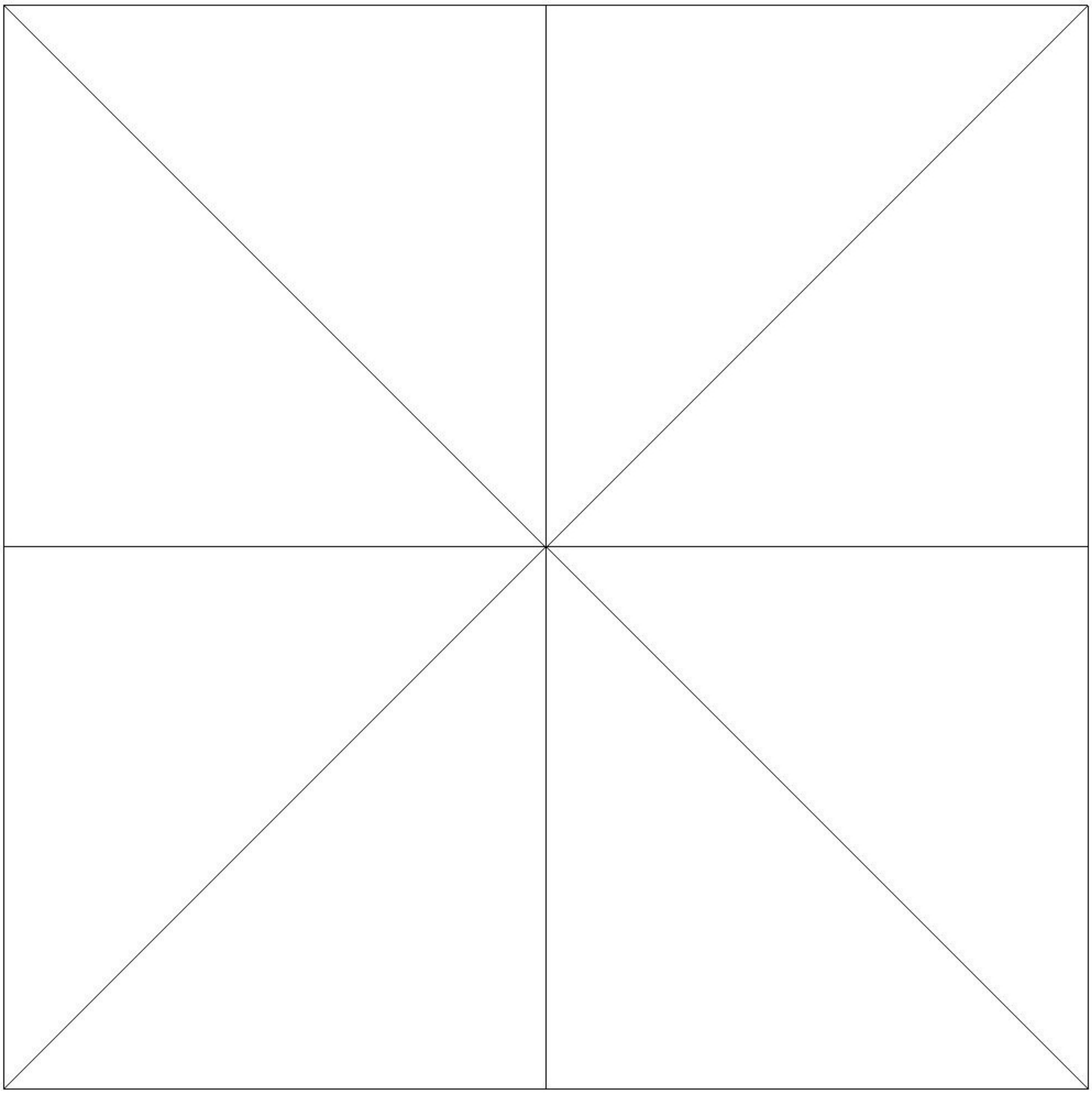
Main tree inventory: 10x10 meter subquadrat map

Plot: ______ **Quadrat:** _______ **Start date:** _____________ **End date:** _____________

Subquadrats (list 4): ____

Field crew: ____

Supervisor: _________________________ Data Entered by: _________________ Date: _________



Chapter VII. Tree height

The volume of wood and hence the carbon mass in a tree depends mostly on the trunk diameter and the tree's height, and thus the most accurate formulae for estimating biomass depend on both measurements. Every trunk's diameter is measured, and ideally every height would be measured, but the height of trees much taller than about 5 meters is much more difficult to estimate. For this practical reason, I suggest measuring the height of a random sample of 10 trees per one-hectare plot. This will be converted into regression formula relating tree height to trunk diameter, as described in the final chapter on data analysis.

A. Selecting trees

Because tall trees carry more biomass, it is important to make sure the regression of height against diameter is based on the range of diameters in the forest (1 cm up to 100 or even 200 cm), and that large trees are well-represented. This can be done by sampling trees from pre-defined diameter categories, as listed in Table VII.1.

One way to select 10 individuals would be to wait until the enumeration teams have mapped and measured all trees in a hectare, then choose one tree randomly from the list of diameter categories. I suggest an alternative here that allows a pair of workers to start measuring heights immediately as the mapping begins. This assumes there are two enumeration teams working in parallel columns, one starting in quadrat 0000 and moving to 0001, 0002, etc., the second starting in 0100 and continuing up the first column. This is the mapping sequence described in Chapter VI, section D.

Table VII.1 Strategy for selecting trees for height measurements at random across a range of diameter categories.

diameter category	tree to measure
1-5 cm	first in 10x10 section where trees < 10 cm are included
5-10 cm	first in 10x10 section where trees < 10 cm are included
10-15 cm	first in quadrat 0101
15-20 cm	first in column 00
20-30 cm	first in column 04
30-40 cm	first in column 03
40-50 cm	first in column 01
50-75 cm	first tree in the full plot
75-100 cm	first tree in the full plot
> 100 cm	first tree in the full plot

The sampling requires taking the first tree of a given diameter category encountered in the specified quadrat or column, as listed in Table VII.1. The reason for the complicated arrangement is to help assure that the sampled trees are not taken from one small part of the hectare. Two field workers responsible for height measurements start work one or two days after the enumeration teams begin. By then, columns 00 and 01 should be finished. The height team checks the data sheets already completed, quadrat by quadrat, to locate trees following the rules listed in Table VII.1. For example, the very first tree in the quadrat 0101 data which is between 10 and 15 cm dbh is selected. To find a tree in the 15-20 cm category, quadrat 0000 is checked, and if there is none, quadrat 0001 is checked, and so on up quadrats of column 00 until the correct diameter is found. The largest three categories are taken from anywhere in the plot, since there are far of these sizes.

If a selected tree has multiple stems, then height should only be measured on the one with stem tag 1 (which is the largest diameter). In this case, the stem tag should be recorded.

B. Height measurement

Trees less than 5-6 meters tall can be measured with a wooden pole marked in meter increments. The pole should be 4 or 5 meters in length. One worker holds the pole next to the tree, and the other stands far enough away to clearly see the tree top and the pole; tree top means the exact highest point on the tree, whether it be leaf, branch, or trunk. Height should be recorded to tenth-meter accuracy.

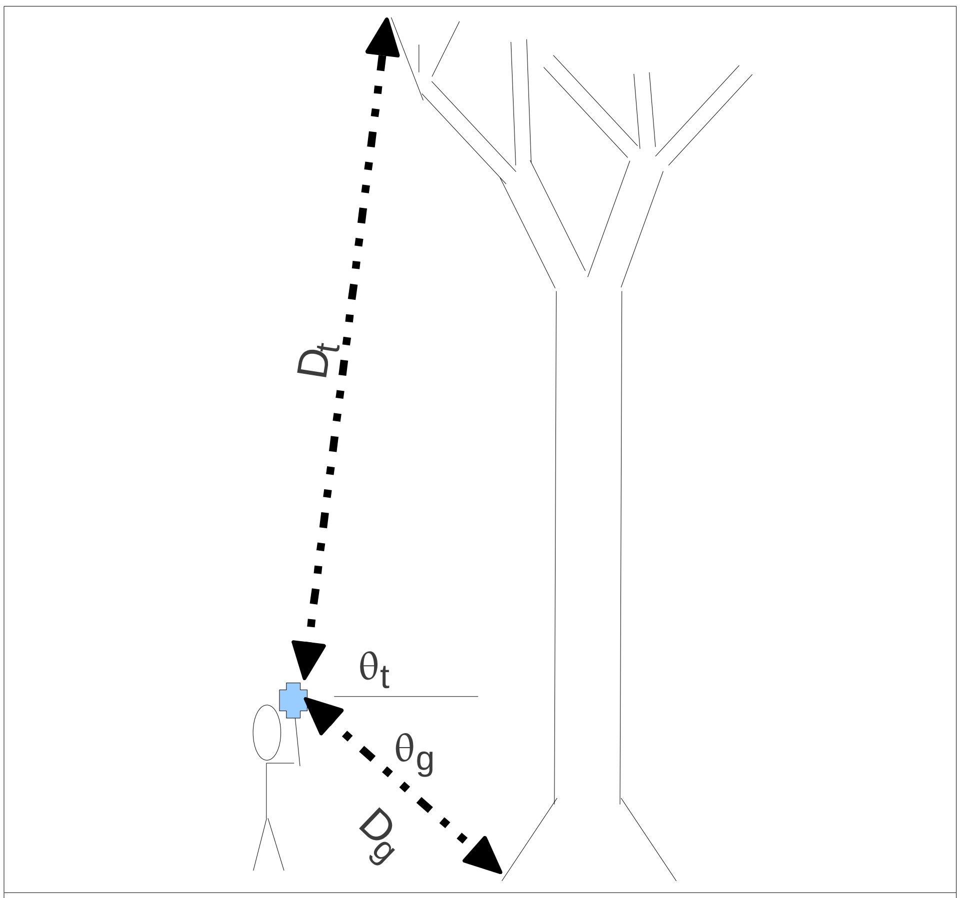


Figure VII.1. Measuring tree height with a laser rangefinder. The point from which the sighting is taken may not be directly below the tallest point on the tree, so the inclination must be recorded. Inclination and distance are also measured to the base of the tree in order to estimate the height of the observer. Inclination from the horizontal to the tree top is symbolized θ_t, and to the ground, θ_g. Distances are likewise D_t and D_g.

Most trees, however, require use of the laser rangefinder. The laser has a precise crosshairs for aiming the laser pulse at a target; both distance and inclination to the target are given with a digital readout. It takes some practice to hit the correct target, given dense vegetation. The strategy is to stand below a tall tree at a spot where the tallest leaves are visible, aiming the laser upward to get the distance to the highest point. This may require multiple laser sightings, taking the greatest distance measured. The field workers should practice on easy-to-sight trees in order to acquire the ability to approximate height by eye. This will help in the forest to be reasonably certain that the very highest leaves or branches are hit by the laser. From exactly the same point where the tree height is measured, angle and distance to the base of the tree must be recorded with the laser rangefinder. The base of the tree is any point where the trunk meets the ground.

C. Dead trees

The height of one dead standing tree per plot, chosen at random from trees > 10 cm dbh, should be measured. If there are no standing dead trees in a plot, this measurement is omitted. If the dead tree chosen is leaning, the height should be measured parallel to the trunk as closely as possible. Recall that the main census includes standing dead trees, so the tree will have a tag number and diameter recorded with the main census data.

D. Tree height data

Height data should consist of a single row of records for each tree measured. Since 10 heights per plot are measured, one form will be sufficient for one plot. At the top of all sheets, the plot number, dates, and names of field workers should be noted. For each tree, the quadrat number, tree tag, and stem tag (only if the tree has multiple stems), plus two heights and two angles need to be entered (see Fig. VII.1). The diameter will be taken later from the main census data (it is better not to re-record the diameter, since this will add errors). If the field team has questions about particular trees, these should be noted in the problem column so the supervisor can quickly note them when reviewing the form.

There is also a column on the field sheet in which to indicate dead standing trees. If the dead tree was leaning, adequate notes must be made to demonstrate how the height was measured.

As an Appendix for this chapter, the following page has a sample data form for recording tree heights. The data sheet names the columns following Fig. VII.1, so a copy of the figure should be taken in the field when heights are measured.

Tree height

Plot: ______ **Start date:** _____________ **End date:** _____________

Field crew: ____

Supervisor: _________________________ Data Entered by: _________________ Date: _________

quad	tag	stem tag[1]	status T/D[2]	D_t	θ	D_g	θ	problem

1 Leave stem tag blank when there are no multiple stems
2 Tree or Dead

Chapter VIII. Wood density

The density of wood in tree trunks holds obvious importance for the amount of carbon held in the forest. Density varies at least six-fold, from light, porous wood that weighs 0.15 g cm^{-3} to species with a density > 1 g cm^{-3}. To estimate total forest biomass, though, only the mean wood density is needed, though the variation will be used to understand error in the estimates. The mean can be found simply by random sampling of trees, even if their species identity is unknown. In addition, the density of dead wood should be measured. Estimates of wood density require the collection of cores of wood from randomly selected trees using a device called a core-borer, designed just for this purpose. Cores must be dried, weighed, and their volume measured.

In the near future, it should be reasonable to omit sampling of wood density from forest inventories aimed at estimating biomass or carbon stocks. Substantial research on tropical forest wood density has demonstrated great consistency in mean density in tropical lowland forests close to 0.6 g cm^{-3} (see Chapter I for research articles). This suggests that more wood density estimates in lowland forests will do little to reduce uncertainty in biomass estimates. Higher elevation forests, however, have lighter wood, and there is less evidence to quantify this. At the moment, I suggest that it is worth measuring density of enough trees in sample plots to generate an estimate of the mean for the forest under study, certainly in forests > 500 m above sea level, but in the near future, this step could be omitted.

A. Selecting trees

Five living trees across a range of diameter categories should be cored in each one-hectare plot. With one exception, these should be the same as trees for which height is measured, so the sampling scheme described in Table VII.1 can followed. The first tree whose diameter is 10-20 cm whose height is measured should be cored, and likewise for diameters 20-50 cm, 50-100 cm, and > 100 cm. Cores should be taken from each of those four trees.

The fifth tree should be a small tree, < 4 cm, the closest tree of this size to the corner stake 0005 (Fig. V.3) but outside the plot. Since the tree is likely too small to core, it should be felled at 1 meter above the ground, and a cookie about 1 cm thickness collected. Even in protected forests, it may be feasible to collect a single tree < 4 cm diameter; if not, this small sample can be omitted. Since this last tree is not inside the plot, its diameter must be measured. A tag should be placed around the cut stump to make sure it can be relocated.

B. Coring

The core borer has large handles allowing it to be rotated into the wood. The core should be horizontal, starting 1 meter above the ground, and as closely as possible, it should reach the center of the tree, but missing by a few centimeters is not a concern.

The vast majority of trees can be sampled without much difficulty. There are, however, trees that are very difficult to core, and if too much force is applied to the borer, it can break, leaving a broken metal tube inside the trunk. With some experience, it is evident when a tree is too hard to proceed. In these cases, the largest possible core should be collected, even if it does not reach close to the center. If very hard trees are skipped, it would obviously bias the estimate of mean density, so it is better to collect a partial core than to skip the tree.

C. Dead trees

From each plot, one core should be taken from one standing dead tree > 10 cm dbh, chosen at random. If there are no standing dead trees, then the sample is omitted.

In addition, one wood sample should be cut out of a single, randomly chosen fallen (and dead) log ≥ 10 cm diameter that was found in the line transect (Chapter X). Exactly where the tree crosses the transect, an entire cookie 5 cm thick should be cut from of the log, then a 5-cm wide section cut from the center of the cookie. If the randomly chosen log is too big to cut across, then a section can be cut from the top, reaching as close to the center as is reasonably possible. Some logs may be so decayed that cutting with a saw is clumsy or impossible; nevertheless, the sample taken should as closely as possible represent a slice of the entire cross section of the wood (see Chapter X). Pieces of wood should not be broken off, because this leads to biased samples of wood (harder than the rest of the trunk): most important is that whatever is collected represent a random portion of the fallen wood.

D. Second cores further above the ground

For one tree per plot, chosen at random from those > 10 cm dbh, a second core should be collected at approximately half the height of the tree above the ground (that is, if the tree is 15 m tall, the second core would be 7.5 m above the ground). If the randomly chosen tree is too tall to sample at half its height, the sample can be taken at 7-8 m. Whatever height is chosen, it should be measured accurately using a tape measure. This will require a ladder, and a safety harness should certainly be used to make sure no one falls.

E. Processing cores

Cores plus samples from dead logs should be stored in ziploc bags. Plot number and tree tag number should be written on the bag or on paper placed inside the bag. For the small tree outside the plot, the diameter must be recorded along with plot number.

In the laboratory, each core is weighed precisely and its volume estimated by water displacement while it is still fresh, within a couple days of collection. An accurate graduate cylinder is filled with water to a precise level, then the wood core held under the water with a pin. The water level is then re-read to determine how much it rose, which is the wood volume.

For dead wood, water displacement is not a good way to measure volume, because there may be pores or gaps into which water can flow. (Those gaps must be included in the volume.) If a core is regular and cylindrical, then the ends should be cut perfectly flat (perpendicular to the long axis), and the length and diameter measured precisely. Samples of decayed wood may not be regular cores, though, and these need to be cut carefully into exact rectangles so their dimensions can be measured.

Then the core must be dried until all the water is gone. It is convenient to leave the core inside a bag or vial, but opened so water can escape, then placed in an over at around 100^{o} C. for four days. To be certain the wood is fully dry, weights should be taken on days two, three, and four, and continuing until no more weight is lost. Once a few cores have been weighed on intermediate days, it becomes evident how much time is needed, and other cores do not require intermediate weights. It is better to leave cores for extra days to be sure, as no damage is done waiting too long. Weights and volumes should be recorded precisely, to tenth-gram (or tenth-milliliter) accuracy. The initial weight should be recorded, although it is not used in estimating wood density, which is simply the final (dry) weight divided by the initial (wet) volume.

F. Wood density data

The data for wood density consists of a single row of records for each sample. For each, the date, tree tag number, height at which the core was taken, wet volume, and dry weight are recorded; the initial wet weight and intermediate weights should also be kept (though they are not used in the final calculation, they are useful to illustrate drying time). Be sure also to include a column of data to indicate dead trees and fallen logs. The diameter will be taken later from the main census data (it is better not to re-record the diameter, since this will add errors); however, for the one small tree outside the plot, stem diameter needs to be recorded, since it does not have a tag nor diameter in the main census. At the top of a form, the plot number and names of field workers should be noted, plus the drying temperature. A single form per plot will suffice. As an Appendix for this chapter, the following page has a sample data form for recording wood core measurements.

Wood density

Plot: ______ **Start date:** _____________ **End date:** _____________

Field crew: ____

Supervisor: _________________________ Data Entered by: _______________ Date: _________ Drying temperature: ______

quad	tag	status L,D,F[1]	diam[2]	core ht (m)	wet vol (ml)	wet wt (g)	wt day 2 (g)	wt day 3 (g)	wt day 4 (g)	dry wt (g)	problem

1 Live, dead, or fallen
2 Only recorded for the one small tree collected outside the plot

Chapter IX. Dead wood

In some forests of the world, fallen dead wood holds a substantial fraction of forest carbon, in some places even more than living trees. Methods for sampling fallen trees were developed in western North America, where large trunks can remain on the ground for decades and accumulate enormous volumes of dead wood. In tropical forests, there is less fallen wood because trunks decay much faster, so the importance of sampling is reduced, but it is still 10-15% of the living above-ground biomass. Sampling is quick and easy: lines are walked and pieces of wood they cross are measured.

A. Locating a line transect

Within all forest plots, a perpendicular line transect is established running the full plot dimensions, 10 m from the west boundary (Fig. X.1). Once the tree census team has finished the first column of quadrats, there will be posts in place every 5 m along this line. It may be helpful in viewing the transect to tie a brightly colored flag to the top of the posts along that line (or perhaps every 4^{th} or 5^{th} post). The northern 10 m of the transect will include samples of smaller pieces of wood then the rest, and is indicated with additional dashing in Fig. X.1.

The illustration shows the transect location for the standard 100x100 m forest plot. In smaller plots, the transect should always be placed 10 m from the west boundary, running north-south. In a plot sized 10 m on a side, the transect coincides with the east boundary.

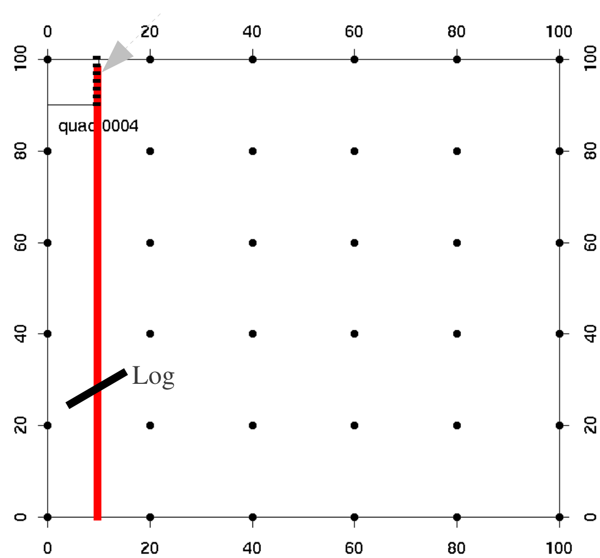


Fig. X.1. Line transect to sample dead wood. The arrow indicates the northern 10 m of the transect, where smaller-sized wood is included.

To reiterate an obvious but important issue: both census and survey teams need to avoid moving or damaging fallen vegetation in the five quadrats of column 00. All the field workers should be aware of the exact location of the transect for fallen wood and know that the northern 10 m is the only section where small branches and stems are included. Then proper attention can be paid in the relevant quadrats, and fallen wood can be ignored in the rest of the plot.

B. Surveying the transect

Two field workers walk the transect to locate fallen tree trunks or branches which intersect the line. Since stakes are already placed every 5 m, this should be possible by eye. One person stands at the first stake and sights carefully from there to the next stake, locating the precise point at which any trunk, branch, or fragment of fallen wood intersects the imaginary stake-stake line. The second worker places a straight pole horizontal over the trunk at precisely the intersection point, orienting the pole along the transect, exactly north-south (Figs. X.2, X.3). The first worker provides directions. Use of a string to stretch between stakes and a compass to orient the measuring stake make the task easier, but greatly slow the work; two people sighting by eye should have no trouble being accurate enough.

The diameter of the trunk is then measured: the width perpendicular to the longest axis of the wood fragment, as close as possible to the transect (Figs. X.2, X.3). Only if this diameter is ≥ 10 cm is the wood included. In the last 10 m of the transect, the minimum diameter changes to 1 cm. The diameter is best measured with calipers.

All pieces of wood counted should be tagged; in most large pieces, the tag can be attached with a nail; for smaller branches, tying with a string is probably best. Tags may fall out quickly as wood decays, but the main purpose is to allow logs to be relocated in the next few weeks, in case problems are identified during data entry.

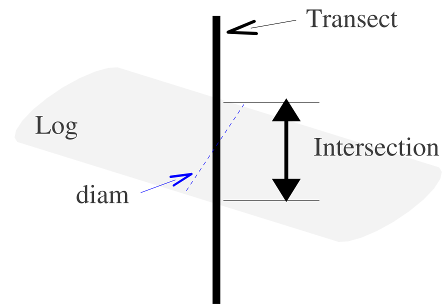


Fig. X.2. A log lying on the ground as viewed from directly above. The transect would be marked by the string held taught immediately above the log. The intersection of the log with the transect is measured along the string. The diameter is measured perpendicular to the long axis of the log.

For each log, the 20x20 m quadrat should be noted (see Fig. V.3 for quadrat numbering). Within each quadrat, the position along the transect should also be recorded, that is, the distance in meters from the baseline of the quadrat. Since stakes are placed every 5 m, this can be easily calculated by finding the nearest 5-meter stake then estimating by eye its distance to the log. In Fig. X.1, a log is indicated in quadrat 0001, at position 8 m: the distance from the line marking the south end of its quadrat. Position can be recorded to the nearest meter.

The two important measurements on each piece of wood are the length of the intersection of the transect with the log and the height of the top of the log at the transect. The intersection is measured while holding a pole in place above the log (on the transect), then using calipers held at the correct angle. Note that the intersection will be greater than the diameter unless the log is precisely perpendicular to the transect (then intersection = diameter).

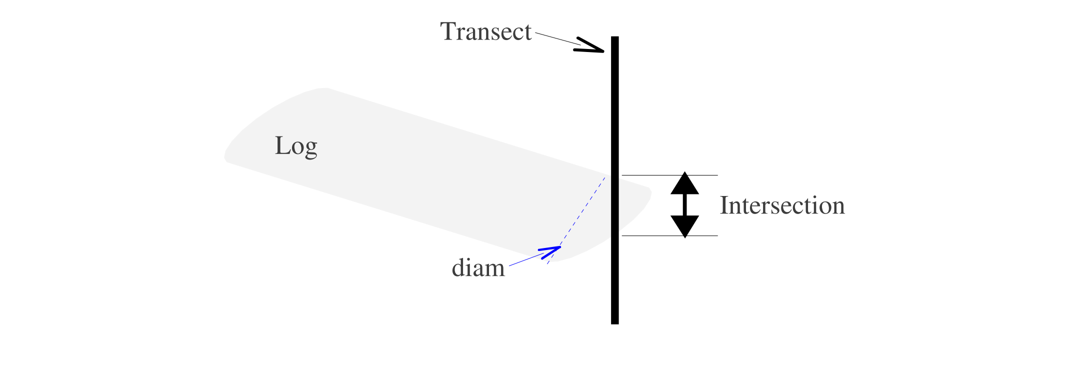


Fig. X.3. A log lying on the ground as viewed from directly above in a case where the transect meets at an irregular end. The intersection is always precisely defined as where the transect is over the log. The diameter should be measured as close as possible to the transect.

The height is best measured by placing a vertical pole next to the log, then measuring with a tape from the ground to the spot level with the high point of the log (Fig. X.4). The latter can be located by eye, holding one's eye level with the top of the log). Height, intersection, and diameter should be recorded to the nearest millimeter.

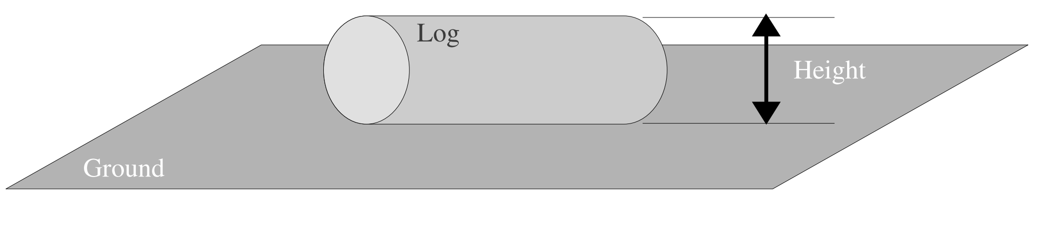


Fig. X.4. This is a diagram of a log lying on the ground as viewed from the side. The height is refers to the distance from the highest point of the log (above the ground) exactly where the transect meets it.

Logs may be irregularly shaped, broken, highly decayed, or the transect may intersect near the end (Fig. X.3). In all cases, the intersection is precisely where the transect meets the log. The diameter on the other hand is always perpendicular to the longest axis, as close as possible to the transect. Both height and diameter may be difficult to define on highly decayed, irregularly-shaped logs. It is then up to the field team to record measurements that best indicate of the size of the log.

C. The data

There should be one field sheet per plot, with plot number, names of the field crew, and date recorded at the top. Blank lines to record the names and dates of data entry should be included. Each individual log found along the transect has information recorded on one row: quadrat, position within quadrat, diameter, intersection, and height. As an Appendix for this chapter, the following page has a sample data form for recording the survey of fallen dead wood.

Fallen dead wood

Plot: ______ **Start date:** ______________ **End date:** ______________

Field crew: ____

Supervisor: ___________________________ Data Entered by: __________________ Date: __________

quad	tag	position (m)	diameter (mm)	intersection (mm)	height (mm)	problem

Chapter X. Replacement Vegetation

Part of the equation for documenting carbon protected within a forest involves estimating the amount of carbon that would remain after the land were deforested: the vegetation expected to replace the forest. The only reasonable way to make this estimate is to sample nearby sites that have already been deforested. Typical replacement vegetation in tropical areas would include tree plantations, cattle pasture, or other food crops; most often these are mixed with isolated fragments of remnant forest. In Chapter VI on forest plots, I described how to sample the remnant trees and plantations. Here I cover methods for sampling non-forest vegetation, either small shrubs or herbaceous ground cover.

The general principle is much different than in forests. Instead of measuring an indirect indicator of plant biomass -- tree height and diameter -- and converting to carbon, plants will be simply be weighed directly. Another contrast may also be land ownership, since non-forests are most often in private hands. I assume in what follows that adequate permission can be achieved for removing small samples of vegetation for the analysis.

A. Site selection

In Chapter IV, I described methods for site selection and mentioned that the individual sampling units in non-forest are 1x1 meter square quadrats at three corners of 20x20 meter squares. There should be a total of 30 such 20-m quadrats, for a total of 60 1-m sampling squares. These should be chosen from non-forest locations, as defined at the outset with satellite or aerial photos, and stratified across elevation and climatic gradients. Although this may seem a fairly small number, grass- or cropland has very low biomass compared to forest, and the estimate does not need to be especially precise. The 30 sites should be chosen from maps, before entering the field.

Once a selected site is reached in the field, team leaders should follow the same procedure for locating the precise location as I described for forest plots (Chapter IV). In most situations, a stake should be put in the ground at the precise, predetermined location. But some circumstances may make the precise location inaccessible: perhaps it turns out to be forest, or a highway, or a vertical cliff. Only when utterly and unequivocally inaccessible should the leader follow the protocol for relocating. This is the same for forest plots: first move precisely100 meters north, and if this fails, east 100 meters (etc etc). When a site is determined to be accessible, the base stake is placed.

B. Surveying

Since the sampling region will be only 20x20 meters, surveying is an easy matter, and can be done with a tape measure. Nevertheless, it should be done exactly, with four corner stakes placed on the four corners of the quadrat, and the quadrat laid precisely in cardinal directions (ie, north-south). At three of the corners, the square meter inside the 20x20 m quadrat should then be demarcated. The corner where the base stake was placed is not sampled. Thus, northeast, northwest, and southeast corners are sampled, not the southwest.

Ideally, the base stake, or all four stakes, would be left as permanent markers, pounded deep in the ground and marked with a metal cap for future location with metal detectors (see Chapters V and XIII). If this is not feasible on private land, then stakes cannot be left. Regardless, precise GPS coordinates should be recorded for the base stake.

Placing the 1x1 sample units is best done with a pre-constructed square whose inner dimensions are exactly 1 meter on a side.

C. Vegetation sampling

The goal then is to remove every shred of vegetation in the 1-m square, excluding only woody stems ≥ 10 mm dbh. All of it will be weighed. Any reasonably effective cutting device can be used, as long as the plants are cut flush to the ground. The vegetation should then be cut into pieces whose size is convenient for loading in bags, and wood parts should be separated from non-wood. At this stage, nothing should be lost: all vegetation must be weighed.

The wood and non-wood components should be loaded in two separate plastic trash bags, or any other large and easy to use container, and carried to a spot where a scale can be used. This is the total wet biomass, taken in two components -- wood and non-wood.

The only plants not cut and weighed are woody plants with a dbh ≥ 10 mm. These stems are should have height and dbh measured following the methods for tree plots. They should be given tags as well to facilitate relocation. But note that 1x1 m plots are very small, and it is likely that no trees at all will be encountered.

Now subsamples of wood and non-wood sections need to be collected haphazardly for drying. Approximately 1 kg of the non-wood component should be collected at random from the large bags and placed in smaller containers for returning to the lab. Three sections of woody stems or branches should also be collected, each a few centimeters long. The wet weight of each subsample needs to be recorded. They will be returned to the laboratory, dried, and reweighed.

Since a variety of plant debris are mixed in, drawing a truly random sample for drying is a challenge. The entire mass (of each component) should be mixed by tossing on the plastic sheet, then handfuls can simply we swept out into a bag. The issue of random samples for drying can of course be bypassed by drying the entire mass from a 1x1 meter quadrat, but this may produce such large volumes that drying would be impractical. However, I suggest again that the estimate for non-forest biomass need not be so precise, so that the approach I have described will be adequate.

D. Laboratory processing

The goal is to get a dry weight for each sample, which should be accomplished by drying at 100^{o} C. for four days. The wood pieces are handled just as wood cores from trees (Chapter XIII, section E). Non-wood samples, which are presumably mostly leaves and soft stems, are best dried in mesh bags that prevent any of the sample from being lost but allow moisture to escape. Initial samples should be weighed at days two, three, and four to determine how long it takes to reach constant mass; once known, intermediate weights are not necessary.

E. Trees in non-forest

Trees planted in rows along roads or fences, or isolated in fields of non-tree vegetation, cannot be counted using standard forest plots. Instead, aerial photos should be used to count trees over larger areas (Chapter IV). The methods for working with aerial photos is outside the scope of this document.

A set of trees identified in the photos should be chosen at random, and heights and diameters measured following the standard methods of Chapter VI. A total of 200 remnant and fence-row trees across the study region should be selected from the photos for these measurements.

F. Data

For each quadrat of 20x20 m, there will be three 1x1 m samples. Each of these 1x1 m subquadrats has two different wet weights collected in the field (wood and non-wood components). Then two subcomponents are collected from each, and these are weighed immediately and then again when dry.

There may also be woody plants with stem dbh ≥ 10 mm dbh measured inside the 1x1 m samples. I also suggest that a description of each plot in non-forest vegetation be provided: what kind of vegetation, how tall, etc.

Other trees selected from aerial photos will also be measured. The data for these trees is similar to data from standard tree censuses, including tag, stem tag, dbh, HOM, and codes; in addition, instead of plot and quadrat numbers, the GPS coordinates of every tree should be recorded. These trees should be assigned a plot number for keeping track in the data.

As an Appendix for this chapter, the following three pages provide sample data forms for the replacement vegetation plots. The first page is for the vegetation samples in 1x1 m subquadrats, of which there are three per plot, and includes a section for wet and dry weights. The second page covers any trees found in the subquadrats. The final page is for the sample of trees selected from aerial photos, and is essentially identical to the form for recording tree measurements inside forest plots.

Replacement vegetation plot

Plot: ________ **Start date:** _____________ **End date:** _____________

Field crew: ____

Supervisor: _________________________ Data Entered by: _________________ Date: _________

GPS coordinates of 4 corners: __________ ___________, __________ ___________,

__________ ___________, __________ ___________

Description of the vegetation:

Wet and dry weights of vegetation in 1x1 m subquadrats

	subquadrat 1		subquadrat 2		subquadrat 3	
	wood	non-wood	wood	non-wood	wood	non-wood
total wet weight (g)	_______	_______	_______	_______	_______	_______
subsample wet weight (g)	_______	_______	_______	_______	_______	_______
subsample day 2 weight (g)	_______	_______	_______	_______	_______	_______
subsample day 3 weight (g)	_______	_______	_______	_______	_______	_______
subsample day 4 weight (g)	_______	_______	_______	_______	_______	_______
subsample final (dry) weight (g)	_______	_______	_______	_______	_______	_______

Replacement vegetation plot

Plot: ________ **Start date:** _____________ **End date:** _____________

Field crew: ____

Supervisor: _________________________ Data Entered by: _________________ Date: _________

Trees inside the 1x1 m samples

sub-quad	tag	stem tag	status T/D/L	diam (mm)	HOM (m)	codes	comments	prob
_,_	___________	___	______	_______	_____	________	____________________________	___
_,_	___________	___	______	_______	_____	________	____________________________	___
_,_	___________	___	______	_______	_____	________	____________________________	___

Non-forest tree inventory
Isolated trees chosen randomly from aerial photos

Plot: ______________ **Date:** ______________

Field crew: ____

Supervisor: _________________________ Data Entered by: _________________ Date: _________

GPS x,y	tag	stem tag[1]	diam (mm)	HOM[2] (m)	codes	comments	prob
,							
,							
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,							
,							
,							

1 Leave stem tag blank when there are no multiple stems

2 Leave HOM blank when it is the standard 1.3 m

Chapter XI. Independent validation

Any large scale project whose purpose is an accurate estimate of carbon stocks, along with an indication of the confidence in that estimate, should at least consider having experts not associated with the project visit the site and evaluate all aspects. To be truly independent, the outside experts should have prior knowledge about appropriate methods: they should not consult this document, but rather develop their own evaluation. For this reason, I cannot present details of validation methods.

If I were consulted to assess another project, I would interview supervisors and field workers, examine sample data sheets, and remeasure a sample of survey lines and trees to check for accuracy. How many remeasurements I made would depend on the resources the project developers wanted to invest in validation: to be really thorough, I would collect 200 remeasurements of survey lines, diameters, heights, and wood densities and compare my numbers precisely to those already collected. I would also consider using methods very different from the original methods: aerial flights to estimate tree height, for instance. A sufficient number of measurements made by a completely independent expert would assist in judging the confidence of the carbon estimates (see Chapter XIII).

Chapter XII. Data Input

My methods for data entry are from the pre-palm-pilot world: data are written with pencil on sheets of paper in the field, and later transcribed by clerical personnel whose primary skill is reading and typing (not field biology). Palm-pilots and even full-sized field laptops are now in use, but among the biologists I know, there remains a schism between those who prefer to get the numbers on paper and those who swear by field computers. It seems inevitable that most will switch to field computers in the next few years, though, obviating the steps outlined here: transcribing data off paper forms into computer systems.

A. Specialized data entry software

Assuming data must be transcribed from field data forms, my foremost recommendation is that specialized data entry systems be developed, catering to the exact format of the data sheets. Most important, a data entry screen on the computer should precisely match the data forms being transcribed: the same columns in the same order, and the same headers at the top. Further refinements include setting up key strokes that allow easy navigation between records, or even automatic filling in of some records. For example, the tree tag number might be automatically incremented by one when a new line is entered.

I have a system for entering tree plot data already devised, and I can make it available to anyone interested. Any student with some programming experience could make small changes to best accommodate the details of another project. As part of a future editions of this document, I will include software matching the data forms provided.

B. Double data entry

My next recommendation is to transcribe all field sheets twice, by two different people. The resulting files can then be compared entry by entry. Discrepancies between the two files are resolved by one of the two checking the entries against the original field sheets. This almost completely eliminates typos, and it also helps overcome problems caused by poor handwriting (since hard-to-read entries may be typed differently). The data entry software should automatically run comparisons and return lists of discrepancies.

C. The final database

It is beyond the scope of this document on field methods to provide details of a design for the database. But I will outline a few suggestions, trying to help avoid a few simple errors. Indeed, most field biologists store data using poor techniques that lead to a proliferation of unnecessary errors. The principle behind the outlined methods is to store data in separate tables, with each table covering one well-defined object, whether that object be trees, stems, measurements, plots, or people. Below is a list of tables that I routinely use for storing plot data.

1. Table of plots. Each plot appears once, along with any plot information which never changes. In particular, the GPS coordinates of the plot and the plot size appear in this table.

2. Table of personnel. The name of each person on the project appears on one row in this table.

3. Table of roles. This is an optional table which keeps track of which person worked on which plot and in what capacity. A single record includes a plot number, a person, a role (such as supervisor, enumerator, or data entry), and a census number (the latter only relevant when a plot is recensused).

4. Table of plot censuses. This has a record for each census of one plot. These are stored separate from the plot table because a single plot might be censused more than once.

5. Table of trees. Every individual tree in all the censuses appears once in this table. It has to include plot number and tag number, and also should include information about the specific location (generally, a quadrat number plus precise x-y coordinates within the quadrat as estimated by digitizing the maps). This table does not include measurements, but it includes fields to indicate status (tree, liana, dead).

6. Table of stems. This table is necessary because multiple stems are tallied. It includes a single record for every stem, with tag number and stem number to identify.

7. Table of measurements. This is the core table for plot censuses. It includes a single record for every stem measurement, an indication of the type of measurement (dbh, height, or weight of a wood core), and must include the tree tag and stem tag for identification, the date of measurement, plus the codes associated with the measurement. The reason measurements are not stored in the stem table is that a single stem can have more than one measurement.

8. Table of vegetation weights. Each weight collected in a 1x1 m subquadrat appears once in this table. It must include plot number, subquadrat number, an indication of what was weighed, and whether it is a wet or dry weight. Given the methods described here, there will be six rows for a single quadrat (Chapter X).

All these tables are stored together in a single database. They must be joined to produce useful reports, for example, to generate the diameter measurements from one plot, the tree, stem, and measurement tables must be joined, with only those records for the selected plot included. To include the location of that plot, the plot table would also have to be joined. Additional tables on geographic and remote-sensed information could also be included in the same database.

D. Data screening

Before the data are loaded into the final, production database just described, there are several screening steps that should be carried out. Several of these are crucial for storing data and are thus essential; others may be skipped. I describe these steps after describing the database, because the structure of the database makes it clear why certain errors are critical.

1. Duplicate key fields. The database above relies on several key fields for identifying pieces of data. For example, plots are identified by plot number and trees by their tags. These key fields cannot be duplicated anywhere in the data. What if two trees were inadvertently given the same tag number? It would clearly be impossible to interpret measurements of those trees. All key fields should be screened for duplicates, but the one most frequent error is duplicating tree tags: the entire database has a very large number of trees, and mistyping just one can cause a duplication. It is easy and fast to screen for duplicates, and then it is often easy to resolve the problem by consulting the datasheets. If the duplicates cannot easily be resolved, there are other database methods which can be employed to assure the trees are not confused, but this manual cannot go into further details.

2. Mismatching tags with multiple stems. To run this screening, it is necessary first to assign every tree which has no multiple stems a stem tag of 1. In field sheets, the stem tag for these trees was left blank, and no stem tag was applied. For data purposes, the trees should be given a stem tag. It is then possible to check whether there are tree tags which have stem tags 2 or higher, but lack stem tag 1. Again, these issues can often be easily resolved by checking datasheets.

3. Mismatching tags on maps. Trees are identified on the maps by their tags. Every tag on a map should also appear in the main census forms. Further, since a map covers only one quadrat, each tag on a map must match a tag in the specified quadrat. This is easy to check and typically reveals a number of errors due to mis-recorded tags.

4. Other mismatches. There are a variety of other ways that matching key fields should be screened.

For instance, once a list of plots is typed, then every plot number in the tree table should be matched against it.

5. Illegal entries. Another type of error can be screened simply by checking whether measurements or dates make sense. Diameters are always > 10 or 100, but should never be above 5000 or higher. Weights of wood cores or vegetation can likewise be checked for unreasonably values. Illegal dates are also easy to check.

Running a variety of routine screening procedures removes once and for all a wide variety of errors which can be easily avoided. A good way to do the screening is to build it into the software that compares the two sets of double-entered data. Removing these errors within a few days or weeks of the field work is enormously more efficient than trying to do it years later.

Key issues for data input

Specialized software for data input should provide computer screens that precisely match forms on which data were recorded in the field

Specialized software can also provide routine screening for illegal data

Double data-entry removes most typos

Final data should be organized following strict database principals, preventing many types of errors

Chapter XIII. Closing down a plot

My main topic here is to consider the issue of leaving the plot stakes in the ground. This depends on the status of the site and whether there is permission for leaving permanent markers.

First, I suggest removing all 5-m and 10-m stakes. Ideally, this is done after data are entered in the database and errors screened; until then, the stakes will make it easier to reexamine trees that led to errors in the data.

As to the stakes at 20 m intervals, if there are reasons to continue using the plot after the census is complete, then of course it makes sense to leave the visible, above-ground markers in place. But if no one will be in the plot for a year or more, they too should be removed. After a few years, they will nearly all be knocked over or lost. Ideally, permanent, PVC stakes, sunken so their tops are flush with the ground, will be left in place, with metal tags attached so they can be found later with metal detectors.

The remaining issue with closing down the plot is to clean out flagging material and all equipment. This seems a silly point to raise, but I have on numerous occasions found old markers and other signs of past experiments left in forest plots long after the person responsible had left.

Chapter XIV. Estimating carbon stocks

There are two aspects of this problem, and I only address one here. That is the fairly straightforward step of producing an estimate for just two quantities: the total carbon stored in the forest under study, and the total carbon in the projected replacement vegetation. The second aspect of the problem is the vastly more complex topic of estimating the uncertainty in those estimates, and the details for those calculations are beyond the scope of this document.

A. Total carbon

To use a straightforward statistical phrase, this is the 'single best estimate'. It is also where many projects end. The calculations for this are not especially difficult if the vegetation (forest or non-forest) is homogeneous, however, if climate, elevation, or soil conditions produce substantial variation, then it becomes more complicated. My goal here is to provide an overview of the procedures that should be adequate for someone with a moderate background in data analysis to be able to follow.

1. Tree height. The primary goal is to estimate the height of each tree based on its trunk diameter. The basic model is

$$h = H e^{1-ax^b}, \qquad \text{Eq. XI.1}$$

where x is diameter (in mm) and h is height (in meters). The three parameters, H, a, and b must be fitted using non-linear regression.

But tree height may vary with elevation, climate, and may differ in disturbed forest or forest fragments. Elevation and rainfall should be tested in the model as predicting variables:

$$h = H e^{1-ax^b} + c\pi + d\epsilon \qquad \text{Eq. XI.2}$$

where π is precipitation and ϵ is elevation, with additional parameters c and d describing their impact. Models should also be fitted separately in mature, disturbed, and fragmented forest.

The model fitted using equation XI.2 allows the height of every single tree to be estimated based only on its diameter.

2. Wood density. Call the estimated wood density of each tree ρ, measured in g per cm^3. In order to test whether density varies with elevation, climate, a regression model

$$\rho = \rho_0 + m\pi + n\epsilon \qquad \text{Eq. XI.3}$$

should be fitted for mature, disturbed, and fragmented forest. As in Eq. XI.2, π is precipitation, ϵ is elevation, and ρ_0, m, and n are parameters to be fitted. This produces an estimate of mean wood density for any forest category at all elevations and climates.

3. Above-ground dry weight of trees and plots. Chave *et al*. (2005) conveniently provided equations for estimating biomass from diameter and height. The equations depend on an old system for climatic categories, the Holdridge system defining tropical forest as wet, moist, or dry:

$$AGB = 0.1120(\rho d^2 d)^{0.916} \quad \text{(dry forest),} \qquad \text{Eq. XI.4}$$

$$AGB = 0.0509(\rho d^2 h)^{1.00} \quad \text{(moist forest),} \qquad \text{Eq. XI.5}$$

$$AGB = 0.0776(\rho d^2 h)^{0.940} \quad \text{(wet forest).} \qquad \text{Eq. XI.6}$$

AGB means above-ground dry biomass in kilograms; the other symbols match those in Eqs. XI.2 and XI.3. Height is in meters, diameter in centimeters, and AGB in kilograms. In field measurements, I recommended consistent use of millimeters in recording sizes (but meters for heights), so note the conversion necessary to use these formulae.

These equations have the drawback of requiring a characterization of forest based on rainfall. Forests with at least 2000 mm of annual rainfall and no serious dry season should be considered wet forest, while any forest with a dry season of 4 months or more (ie, four consecutive months with < 100 mm rain) is considered moist. Dry forests have 5-6 dry months. Forests with 1500-2000 mm rainfall and no dry season are probably best called moist, while those with < 1500 mm and no dry season as dry. Unfortunately, these definitions are loose, and a model is needed in which rainfall and seasonality are continuous variables.

For each tree, Eqs. XI.2, XI.3, combined with one of XI.4-6 produce an estimate of total above-ground dry weight for a single tree. Summing over all trees ≥ 100 mm diameter in a one-hectare plot produces a plot-wide estimate. The AGB of trees < 100 mm diameter is calculated for one 10x10 meter section, and this must be multiplied by 100 and added to the sum for trees ≥ 100 mm. For plots smaller than one hectare, the summed AGB should be converted appropriately; so for instance, in a 20x20 meter plot, the total AGB would be multiplied by 25 to give the biomass per hectare. Below, I use the symbol A to mean AGB per hectare.

4. Above-ground biomass of the forest. The simplest calculation would involve finding the mean per-hectare AGB of all forest plots, then multiplying this by the number of hectares of forest as estimated from satellite or aerial photos. This calculation is especially appropriate if plots were placed at random across the entire forest, as described in Chapter IV, or in areas that are homogeneous in climate and elevation.

If plots were deliberately placed in different types of forest (mature vs. disturbed and across climatic and elevation gradients), then models need to be developed to test whether the AGB varies with these features:

$$A = A_0 + r\pi + s\epsilon \,. \qquad \text{Eq. XI.7}$$

Here, A is the above-ground biomass of a single hectare, π is precipitation and ϵ is elevation; A_0, r, and s are the parameters to be fitted. Models should be fitted separately in mature and disturbed forest. (This is precisely the same as the model used for wood density.)

Application of the model described by Eq. XI.7 requires precise analysis of satellite (or aerial) photos in order to estimate how many hectares of mature and disturbed forest there are as a function of elevation and precipitation. This could be done, for instance, by dividing the forest up into elevation and precipitation categories, and for each category, apply Eq. XI.7; these are summed to produced the total forest biomass. There are more elaborate GIS methods as well, but I have to leave those to others who work with remote-sensed data.

5. Dead wood. The biomass of fallen wood is estimated using the length of the intersection between the transect and trunks or branches on the ground, as illustrated in Figs. X.2-X.3. Call this intersection i, and the height of the log at the intersection h; note that the diameter is not used in the calculation, only in determining which logs are included in the inventory (diameter ≥ 100 mm, or 10 mm in the last 10 m of the transect). Also needed in the calculation is the mean wood density of fallen logs, ρ_f. The formula for fallen (dead) wood biomass, or DB, is

$$DB = \frac{\pi}{4} \frac{A}{L} \rho_f \sum i h \,, \qquad \text{Eq. XI.8}$$

where *L* is the length of the transect and area is the 10,000 m^2 (or whatever the plot size, in square meters). Two summations must be done, one for logs ≥ 100 mm, with *L* = 100 m, and one for logs ≥ 10 mm, with *L* = 10 m. In both cases, *A* is the total plot size in square meters. If all units are in meters, and wood density in g per cm^3, the result is in tons dry weight. Since I suggested measuring *i* and *h* in millimeters, a conversion to meters is necessary.

The two sums are in turn added together to produce an estimate of the total dry dead weight on the ground, in logs ≥ 10 mm diameter. For plots less than one hectare, this number should be converted to a per-hectare value.

Aggregating across forests can then proceed exactly as described in step 4 above. The model described in Eq. XI.7 should be tested to determine whether dead mass varies with elevation, climate, or forest disturbance.

6. Above-ground biomass of non-forest. In vegetation with trees, including remnant forests and plantations, calculations of AGB proceed as described above. In addition, the methods described in Chapter IV called for placing sampling plots in various types of non-forest vegetation, and AGB in those plots must be calculated differently.

In grassland, cropland, or shrubland, AGB was calculated per square meter samples by weighing all vegetation wet then converting to dry weight using the dried samples (Chapter IX, Section D). Values of AGB on a per-meter basis should then be used in the model of Eq. XI.7 to determine climate or elevation effects; separate models for different types of vegetation (grass, crop, shrubs) should be fitted.

To estimate total biomass of potential replacement vegetation requires a precise prediction about the vegetation that would replace the forest. How much would be crops, plantations, etc? Making that prediction is beyond the scope of the methods described here. Once the prediction is made, the estimate AGB per square meter is multiplied by the projected land area for each type of replacement vegetation, and the sum of all types produces the desired total.

5. Carbon. The dry weight of plant tissue is very consistently 48% carbon, so the final step in estimating carbon stocks is multiplying AGB by 0.48. All plant tissue falls between 45-50% carbon, so this estimate is reasonable for all dead, live, and non-wood samples.

B. Estimating uncertainty

All calculations behind Eqs. XI.1 to XI.8 involve uncertainty, owing to two sources. One is measurement error: plot size, height, diameter, the count of trees, and dry weights are all measured with error. The second is variance around the regression models. Both sources of uncertainty must be propagated into the final estimate of biomass and carbon stock. The full calculations of uncertainty require advanced statistical methods which I cannot cover in thismanual; the best approach is Bayesian, although bootstrapping is a good alternative and somewhat easier to learn and to understand. In future editions of this manual, I will offer details along with software that carries out the analyses.

Chapter XV. Literature

Chapter I provides a brief list of articles on methods of biomass estimation. All those articles are included here, along with additional artilces cited in subsequent chapters.

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