HAWASSA UNIVERSITY

WONDO GENET COLLEGE OF FORESTRY AND NATURAL RESOURCES

TRAINING MANUAL ON:

FOREST CARBON POOLS AND CARBON STOCK ASSESSMENT IN THE CONTEXT OF SFM AND REDD+

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SECTION-I: FOREST CARBON POOLS AND CARBON ACCOUNTING

1. The Global Carbon Cycle

During geological history, the emergence of plants on earth has led to the conversion of carbon dioxide (CO_2) that was in the atmosphere and oceans, into innumerable inorganic and organic compounds on land and in the sea. Natural exchange of carbon (C) compounds between the atmosphere, the oceans and terrestrial ecosystems is now being modified by human activities that release CO_2 from fossilized organic compounds ('fossil fuel') and through land use changes. The earth is returned to a less vegetated stage of its history, with more CO_2 in its atmosphere and a stronger greenhouse gas effect trapping solar energy
By far the greatest proportion of the planet's C is in the oceans; they contain 39.000 Gt out of the 48.000 Gt of C (1 Giga ton (Gt) = 10^9 t = 10^{15} g). The next largest stock, fossil C, accounts for only 6.000 Gt. Furthermore, the terrestrial C stocks in all the forests, trees and soils of the world amount to only 2500 Gt, whilst the atmosphere contains only 800 Gt. The use of fossil fuels (and cement) releases 6.3 Gt C yr^{-1}, of which 2.3 Gt C yr^{-1} is absorbed by the oceans, 0.7 Gt C yr^{-1} by terrestrial ecosystems and the remaining 3.3 Gt C yr^{-1} is added to the atmospheric pool. Fossil organic C is being used up much faster than it is being formed, as only 0.2 Gt C yr^{-1} of organic C is deposited as sediments into seas and oceans, as a step towards fossilization.

The net uptake by the oceans is small relative to the annual exchange between the atmosphere and oceans. Oceans at low latitudes (in the tropics) generally release CO_2 into the atmosphere, while at high latitudes (temperate zone and around the polar circles) absorption is higher than release. Similarly, the net uptake by terrestrial ecosystems of 0.7 Gt C yr^{-1} is small relative to the flux; about 60 Gt C yr^{-1} is taken up by vegetation but almost the same amount is released by respiration and fire.

1.1. Carbon dioxide exchange between Terrestrial Vegetation and the Atmosphere

Organic chemicals are characterized by their carbon chains that along with oxygen and hydrogen form their main contents, with smaller additions of nitrogen and sulfur and some metals. However, life can be said to be dominated by the carbon cycle. In the exchange of carbon dioxide (CO_2) between terrestrial vegetation and the atmosphere, with net accumulation followed by carbon (C) release, the net balance between sequestration and release shifts from minute-to-minute (for example, with cloud interception of sunlight), to a day-night pattern, across a seasonal cycle of dominance of growth and decomposition, through decadal patterns of build-up of woody vegetation or century-scale build up of peat soils out to the stages of the lifecycle of a vegetation or land use system.

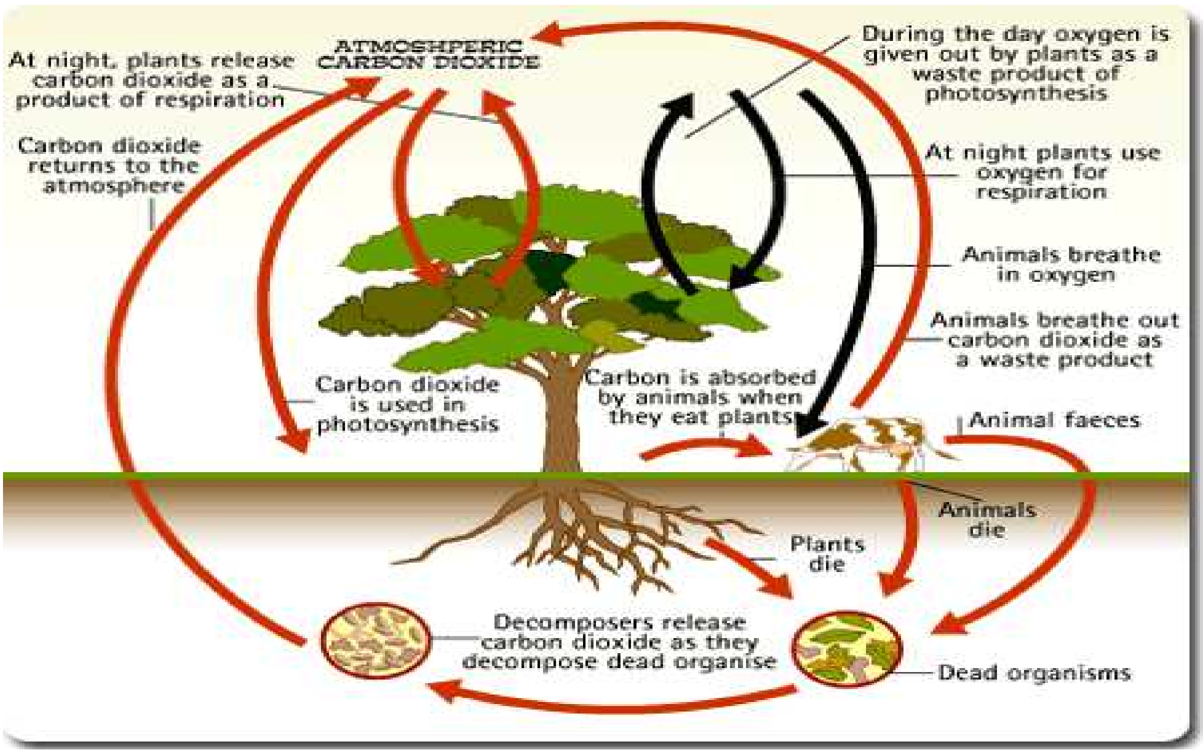


Figure 1: Illustration of carbon cycle at plot level

(Source: http://www.energex.com.au/switched_on/being_green/being_green_carbon.html).

During daytime in the growing season, plants capture CO_2 from the atmosphere and bind the carbon atoms together to form sugars, releasing oxygen (O_2) in the process. At nighttime and at times that plants don't have active green leaves; the reverse process of 'respiration' dominates,

1.2. Annual Carbon dioxide cycles

Through other metabolic processes, plants may convert sugars into starch, proteins, fats, cellulose or lignin in cell walls and woody structures. Most plants will first invest in the growth of roots and stems to allow their leaves to capture more light and capture more CO_2. Once light capture is secured, plants may start to store starch and other organic compounds to survive adverse periods (for example, a dry or cold season) and/or to invest in reproduction through flowers, pollen and seed production. The net balance between photosynthesis and respiration thus shifts during an annual cycle, and measurements of the net capture or release of CO_2 by vegetation will give different results in different seasons.

Animals obtain their carbon by eating and digesting plants, so carbon moves through the biotic environment through the tropics system. Herbivores eat plants but are themselves eaten by carnivores. Parts of dead plants and organic waste and dead bodies of animals return to the soil, for further steps in decomposition and respiration.

1.3. Buildup of Carbon in Woody Vegetation

Perennial plants live for more than a year and may live for more than 100 years. They continue to build up carbon stocks, mostly in woody stems and roots. Carbon storage increases during the process of vegetation succession, when woody plants take over from herbs and shrubs, and when large trees take over from smaller ones. Ultimately, however, even big trees die and fall down, creating gaps in the vegetation that allow other trees-in-waiting to take over. The C cycle continues, but one has to measure over the life cycle of trees to understand the net balance of sequestration and respiration of natural (or man-made) vegetation.

1.4. Climate Change

Climate describes the weather at a location over a long time; a minimum recording period of 30 years is deemed necessary to account for normal variation. Climate change means more than changes in the weather. The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as *"A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods"*

According to the 4th assessment of the IPCC, released in 2007, evidence of global warming is unequivocal. Observed increases in global average air and ocean temperatures, widespread melting of snow and ice and rising of the global average sea level are among key points in the evidence. The year 2008 was the coolest year since 2000, but it was still the 10th warmest year on record since the beginning of instrumental climate records in 1850. The 100-year linear trend (1906–2005) is now estimated to be an increase of 0.74 ^{0}C [0.56– 0.92 ^{0}C]

The conclusion of the IPCC, based on input from a large numbers of scientists and public consultation is that by the time global warming reaches an increase of 2 ^{0}C, major shifts in oceanic circulation and other feedback systems can occur, which will cause major disruption to the world as we know it. Despite, locally positive effects on food production in the temperate and sub-arctic zone, the net effects on global food production and human health will be negative.

By 2020, between 75 and 250 million people in Africa are projected to be exposed to increased water stress due to climate change. Freshwater availability in Central, South, East and Southeast Asia, particularly in the large river basins, is projected to decrease. By 2020, in some countries, yields from rain-fed agriculture could be reduced by up to 50%. In many African countries, agricultural production, including access to food, is projected to be severely compromised.

In particular, the heavily populated mega-delta regions in South, East and Southeast Asia will be at greatest risk due to increased flooding from the sea and, in some mega-deltas, flooding from rivers. The cost of adaptation could amount to at least 5–10% of the total economy. There is good reason to take this seriously, and the remaining scientific uncertainty is no excuse for not acting now.

1.4.1. What causes Global Warming?

Changes in the global climate are primarily caused by changes in the composition of the atmosphere. The atmosphere influences the balance between incoming radiation from the sun and outgoing heat from the earth. Current understanding of global climate recognizes two major factors of natural variability in climate. These are, the 11-year sun fleck cycle in the intensity of solar radiation and the episodic cooling effects due to volcanic eruptions that cause dust and sulfur dioxide to be projected into the atmosphere. On top of that, a number of effects are due to increased emissions of greenhouse gases and the direct effects of land cover on reflection (albedo).

The dominant effect, however, is the increased emission of greenhouse gases, with carbon dioxide (CO_2) being the main one (Figure2). The main concern relates to greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Human activity has led to the steady addition of CO_2 to the atmosphere and an increase in the atmospheric concentration from 285 ppmv (parts per million on a volume basis) before the Industrial Revolution of the 19th century to 379 ppmv in 2005.

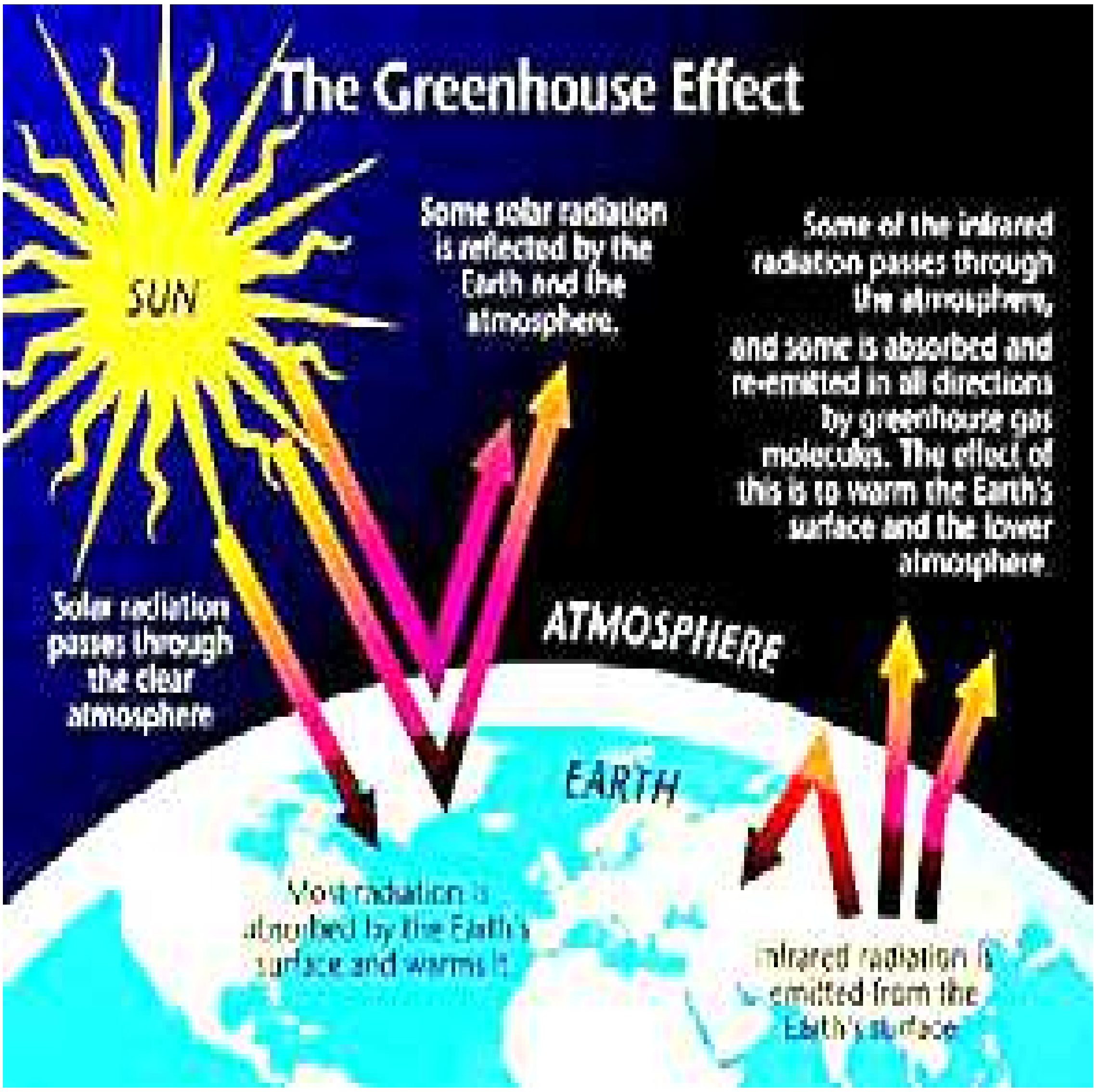


Figure 2: Illustration of solar radiation traveling through the atmosphere on its way to warm the earth's surface.

> *This incoming energy is balanced by infrared radiation leaving the surface. On its way out through the atmosphere, this infra red is absorbed by greenhouse gases (principally water vapor, CO_2 and CH_4) that act as a 'blanket' over the earth's surface keeping it warmer. Increasing the amount of these gases increases the greenhouse effect and so increases the average temperature of the earth's surface. (http://www.mtholyoke.edu/~sevci20l/images/Greenhouse%2520Effect. gif& imgrefurl).*

1.4.2. Human activity and Greenhouse Gas Emissions

About two-thirds of the net increase in atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O and NO) is due to the burning of fossil fuels, in industry, including the production of cement, urban consumption and transportation. The remaining one-third is due to land use and includes releases from carbon stocks in aboveground vegetation (forest) and soils (especially peat soils) that are linked to land use change and to agricultural activities, specifically releasing nitrous oxide (linked to fertilizer use) and methane from livestock and rice paddies.

2. Concepts of Carbon Pools

2.1. Background

Nowadays, there is a growing demand for reliable information on forest and tree carbon stock at both country and global levels. This implies that monitoring the state and changes of forests carbon pools is an important element. Therefore, measuring and estimating carbon stocks and changes in carbon stocks in various pools are very important to carbon trading and marketing. This requires transparent and verifiable methods, quantification of uncertainties and appropriate monitoring systems for carbon stocks. Carbon stock assessment is one of the important step to start with sustainable land use planning in relation to low carbon emission. The change in carbon stock with the dynamics of land use changes may result into either carbon emission or sequestration. This chapter outlines the different carbon pools and the concepts of carbon accounting. It can be used for field practitioners but requires further details on design and measurement protocols.

2.2. Purposes of Carbon Accounting

Thus the overall purpose of carbon assessment includes:

1. to estimate plot level carbon stock at above and belowground carbon pools and develop a comprehensive picture of carbon stocks at regional or country level
2. to calculate the average carbon stock for various land uses systems;
3. to estimate ‘future carbon stocks and emissions under a wide range of forest management and land use scenarios, allowing for a comparison of the emissions, or carbon storage.
4. to assess potential to monetise carbon sequestration and avoided emissions under various domestic and international carbon trading mechanisms.
5. to identify areas of significant uncertainty with respect to estimates of carbon stocks and assess the magnitude of uncertainty and error in estimates.
6. to provide an assessment of likely future stocks and emissions in decadal periods.

2.3. Definition of some terms

Carbon pool: A system which has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, soils and atmosphere.

Biomass: is defined as mass of live or dead organic matter. It includes the total mass of living organisms in a given area or volume; recently dead plant material is often included as dead biomass. The quantity of biomass is expressed as a dry weight or as the *energy*, carbon, or nitrogen content. Therefore, a global assessment of biomass and its dynamics are essential inputs to climate change forecasting models and mitigation and adaptation strategies.

Carbon sequestration: The removal of carbon from the atmosphere and long-term storage in sinks, such as marine or terrestrial ecosystems.

Carbon stock: The mass of carbon contained in a carbon pool.

Biomass density: Changes in time of vegetation biomass per unit area and can be used as an essential climate variable, because they are a direct measure of sequestration or release of carbon between terrestrial ecosystems and the atmosphere. Therefore when using the term "biomass" we refer to the vegetation biomass density, that is mass per unit area of live or dead plant material.

Unit of measure is g/m2 or multiples.

Carbon: is the term used for the C stored in terrestrial ecosystems, as living or dead plant biomass (aboveground and belowground) and in the soil.

$$C = (0.50)*biomass$$

This means about 50% of plant biomass consists of Carbon.

To convert carbon in to CO_2, the tones of carbon are multiplied by the ratio of the molecular weight of carbon dioxide to the atomic weight of carbon (44/12).

Carbon sink: is a carbon pool from which more carbon flows in than out:

Forests can act as sink through the process of tree growth and resultant biological carbon sequestration.

Activities like afforestation, reforestation (AR), sustainable forest management (SFM), Conservation and Enhancement of forests acts as carbon sinks.

Carbon source: is a carbon pool from which more carbon flows out than flows in:

Forests can often represent a net source of carbon due to the processes of decay, combustion and respiration. Activities like deforestation, forest fire and forest degradation acts as sources of carbon.

Therefore, forests can switch between being a source and a sink of carbon over time depending on the type of activity they are experiencing. As both carbon sources and sinks, they have the potential to form an important component in efforts to combat global climate change. That is why forests play an important role in the global carbon balance.

However, the focus of carbon accounting is always on the net changes in the carbon stock, as the 'bottom-line' of many influx (gain) and efflux (loss) processes.

Net Emission Reduction: Indicates the expected amount of emissions reductions that will be generated by the project activities on a certain period of time. It's necessary to stress that, in many projects that are still in design phase, these numbers can be very preliminary and may change in the future.

3. Forest Carbon Pools

According to the IPPC (2006), carbon pools in forest ecosystems comprises of carbon stored in the living trees aboveground and belowground (roots); in dead matter including standing dead trees, down woody debris and litter; in non-tree understory vegetation and in the soil organic matter. When trees are cut down there are three destinations for the stored carbon- dead wood, wood products or the atmosphere. The decreased tree carbon stock can either result in increased dead wood, increased wood products or immediate emissions. Dead wood stocks may be allowed to decompose over time or may after a given period, be burned leading to further emissions. When deforestation occurs, trees can be replaced by non-tree vegetation such as grasses or crops. In this case, the new land use has consistently lower plant biomass and often soil carbon, particularly when converted into annual crops.

Forest carbon pools can be grouped as key categories or minor categories based on ecosystems and land-use changes. Key categories represent pools that could account for more than 25% of the total emissions resulting from deforestation or degradation. In all cases it makes sense to include trees, as trees are relatively easy to measure and will represent a significant proportion of the total carbon stock. The remaining pools represent varying proportions of total carbon depending on local conditions. If the pool is a significant source of emissions as a result of deforestation and degradation, it is worth including in the assessment. Below is a representation of relative percentage proportion of carbon stocks in each pool (Zerihun et al. 2012).

1. Aboveground biomass (15-30%);
2. Belowground biomass (4-8%);
3. Woody necro-mass (1%);
4. Organic litter (0.4%);
5. Soil (60-80%).

- **Aboveground biomass (AGB)-**all woody stems, branches and leaves of living trees, creepers, climbers and epiphytes as well as understory plants and herbaceous growth.
  - Above-ground biomass: all living biomass above the soil including stem, branches, bark, seeds, and foliage.
- **Necromass-**includes dead fallen trees and stumps, other coarse woody debris, the litter layer and charcoal (or partially charred organic matter) above the soil surface.
  - **A) Dead organic matter-wood (DOM)**: includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil.
  - **B) Dead Organic matter-Litter (DOM)-** includes all non-living biomass with a diameter less than a minimum diameter chosen by a given country (for example 10 cm), lying dead, in various states of decomposition above the mineral or organic soil. The original material (e.g. needles) should still be identifiable to be considered litter.

- **Belowground biomass (BGB)-**comprises living and dead roots, soil fauna and the microbial community.
    - living biomass of live roots includes fine roots (< 2 mm diameter), small roots (2 – 10 mm diameter), and large roots (> 10 mm diameter).
- **Soil organic matter (SOM)-**comprises humus and other soil organic C pools in the mineral soil
- **Harvested** wood products (HWP)

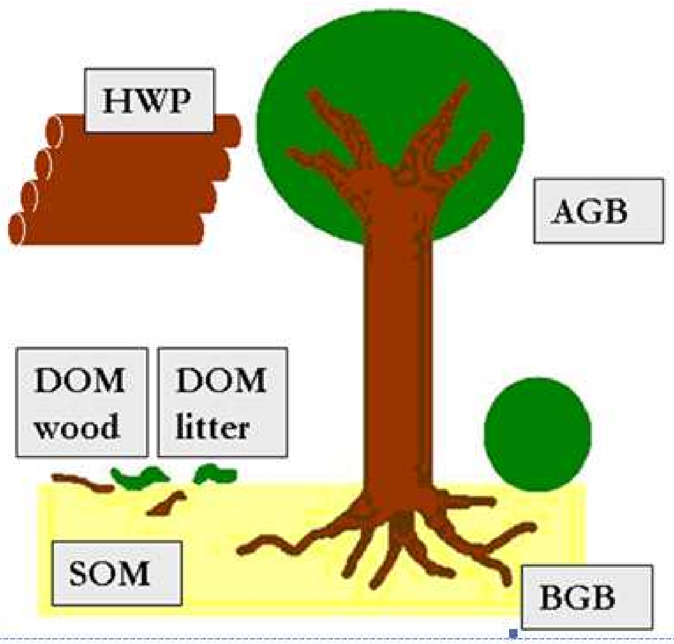


Figure 3: Carbon Pools

Tropical forests in their natural condition contain more aboveground C per unit area than any other land cover type. The main carbon pools in tropical forest ecosystems are the living biomass of trees and understory vegetation and the dead mass of litter, woody debris and soil organic matter.

The carbon stored in the aboveground living biomass of trees is typically the largest pool and the most directly impacted by deforestation and degradation. Aboveground carbon storage in natural forest is higher than that in any other vegetation. Thus, estimating aboveground forest biomass carbon is the critical step in quantifying carbon stocks and fluxes from tropical forests.

Trees often represent the greatest fraction of total biomass of a forested area, with other carbon pools only a fraction of the total tree biomass.

In tropical forest ecosystems,

- the understorey is about 3% of above-ground tree biomass,
- Dead wood 5-40%, and
- fine litter only 5% of that in the above-ground tree biomass.
- BGB is more variable.
- AGB in trees also responds more rapidly and significantly as a result of land-use change than other carbon pools. As a consequence, the majority of carbon accounting efforts are focussed on tree AGB.

Above Ground Biomass (AGB)

- The AGB carbon pool consists of all living vegetation above the soil, inclusive of stems, stumps, branches, bark, seeds and foliage.
- Destructive sampling, whereby vegetation is harvested, dried to a constant mass and the dry-to-wet biomass ratio established.

Below Ground Biomass (BGB)

- The BGB carbon pool consists of the biomass contained within live roots.
- BGB can also be assessed locally by taking soil cores from which roots are extracted
- Ratios with AGB are commonly used for quantifying the BGB

Soil organic matter (SOM)

- SOM includes carbon in both mineral and organic soils and is a major reserve of terrestrial carbon.
- In SOM accounting, factors affecting the estimates include the depth to which carbon is accounted, commonly 30cm.

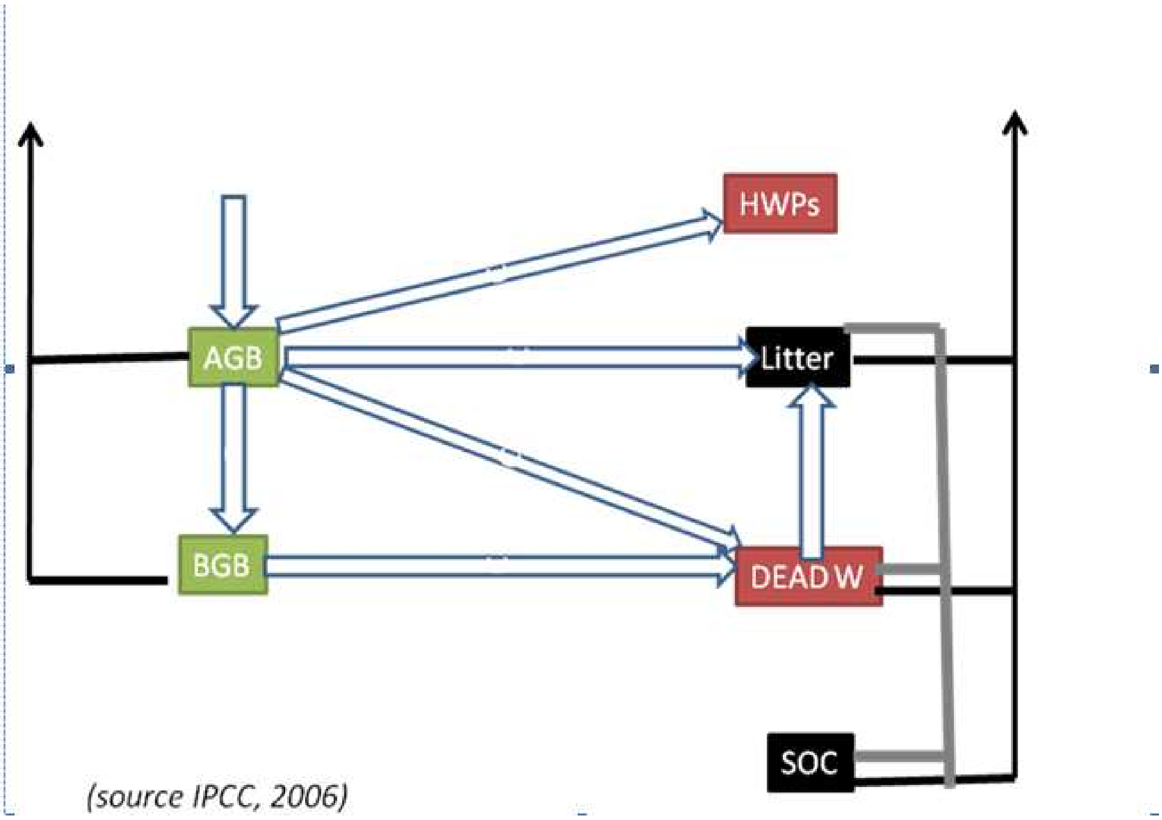


Figure 4: Generalized flow of carbon between pools

3.1. Carbon Accounting

Carbon accounting is the practice of making scientifically robust and verifiable measurements of net GHG emissions. Although there have been many inventories for various purposes (determining merchantable timber volumes, land use planning). Accounting for carbon is a more recent addition to forest inventories. It followed the growing need to quantify the stocks, sources and sinks of carbon and other GHGs in the context of anthropogenic impacts on the global climate.

Carbon accounting varied globally and the net accounting result is positive in tropical regions than the sub tropical and temperate regions (Figure 1. and 2). However, this should not undermine the contribution of GHG emission from deforestation, forest degradation and land use change in the tropical regions.

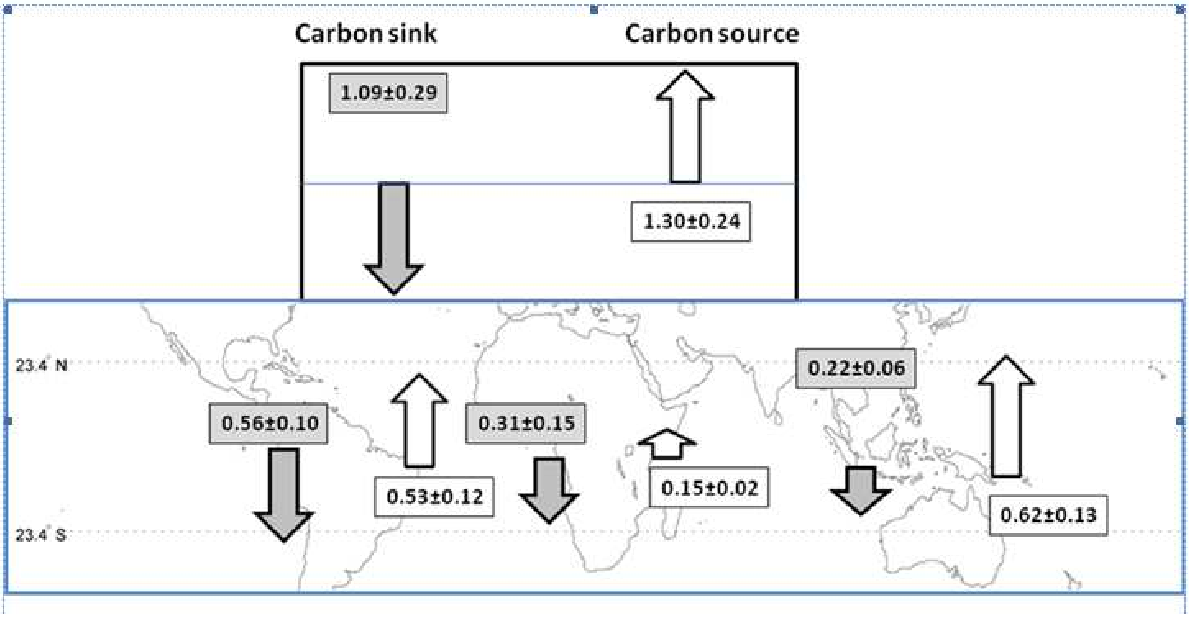


Figure 5: The carbon budget of Tropical land regions: 1990-2005

(Source: Malhi (2010), Current Opinion in Environmental Sustainability)

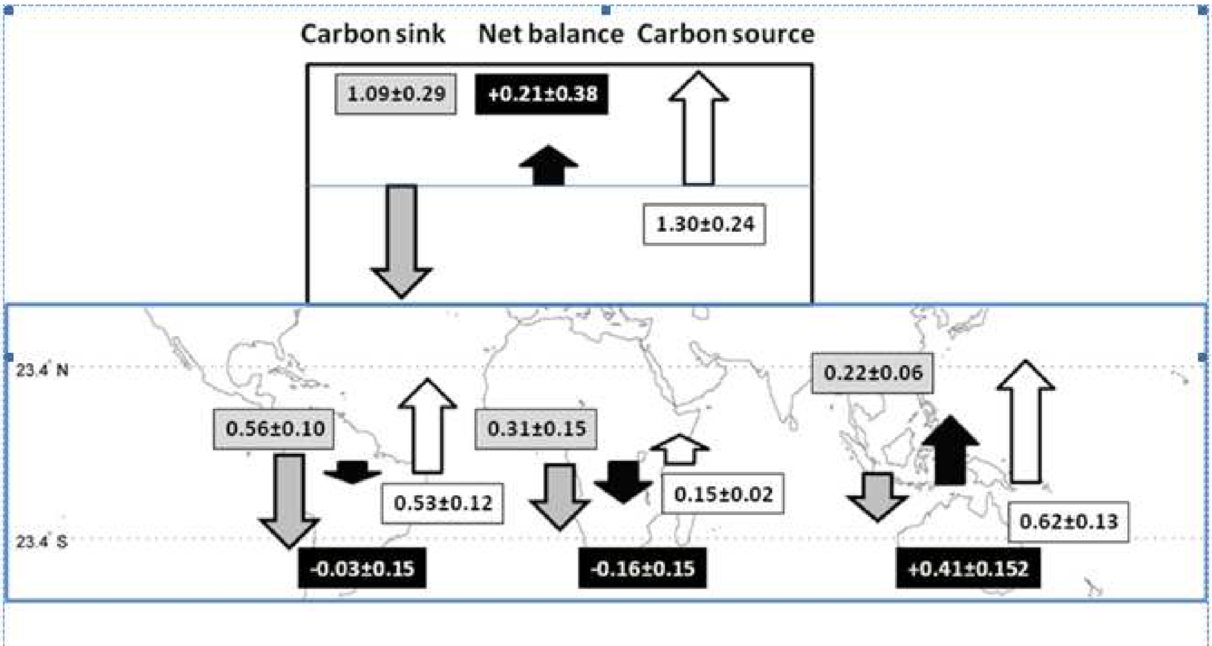


Figure 6: The carbon budget of Tropical land regions: 2000-2005

3.2. Forest Carbon accounting

Forest carbon accounting identifies the carbon-density of areas, providing information for low-carbon-impact land use planning. It prepares territories for accounting and reporting of emissions from the forestry sector. It allows comparison of the climate change impact of the forestry sector relative to other sectors, as well as allowing comparison between territories. Finally, it enables trade of project emission reductions on carbon markets and for emission reductions to be included in policy targets.

Good practice in forest carbon accounting must be adhered to. In particular, transparency in methods and accuracy and precision in accounting are required for public and political acceptance of resultant estimates. A basic knowledge of the principles underlying forest carbon accounting is also beneficial. Understanding biomass dynamics and flows between carbon pools in forest ecosystems enables more effective accounting.

The practice of forest carbon accounting requires clear identification of the accounting boundary in both space and time. Stratifying the forest into areas with similar carbon characteristics further improves the accuracy of carbon accounting. Data for accounting can be gathered from a variety of sources, including existing secondary data, remotely sensed data and primary data through field surveys. The amount of data from each source depends on the quality of the source as well as the trade-offs that must be made between accounting accuracy and costs of resources and time.

All forest carbon accounting estimates contain uncertainty. Practitioners should identify, minimize where possible, and quantify this uncertainty through statistical analysis, published information and expert judgment. The existence of substantial uncertainty can undermine efforts to reduce carbon emissions from forestry and can erode political support for the accounting process. Forest carbon accounting guidance from the Intergovernmental Panel on Climate Change (IPCC) has become the primary source of information for methods, accounting equations and parameters. IPCC, Good Practice Guideline requires data to be:

Adequate,

- *Data that is, capable of representing land use categories, and* conversions between land use categories, as needed to estimate C stock changes and greenhouse gas (GHG) emissions and removals;

Consistent,

- *Data that is, capable of representing land use categories* consistently over time

Complete,

- *which means that all land within a country should be included,* with increases in some areas balanced by decreases in others for estimating and reporting emissions and removals of greenhouse gases; and

Transparent,

- *that is data sources, definitions, methodologies and* assumptions should be clearly described to be verified.

Forest carbon stock accounting is important to determine the carbon stock in the project baseline, to develop project idea note (PIN) and project design document (PDD), to validate, register and implement emission reduction measures. Once the sampling points are identified and all preparations are finalized, the task will be conducting carbon stock accounting in the field. Depending on the project requirements, some of the pools can be omitted, but in this manual, users shall be taken through specific steps in generating data for all the carbon pools.

Steps

1. Familiarize the field team with the field tools and equipment and provide training in advance
2. Locate the first sample plot 50 m into the forest from the edge of the forest
3. Take GPS reading at all corners including compass reading for permanent sample plots
4. Take correct compass reading to the next corner point of the sample plot. Use ranging poles for accurate compass reading to the corner point
5. Lay the nested plots at two opposite corners of the principal plot (this will be explained in the methodology chapter).
6. Collect data on all carbon pools (above ground -woody and non-woody, litter, soil and below ground) or for the carbon pools of your interest and label them

7. Calculate the biomass for each carbon pool
8. Calculate the aggregate carbon stock for the sample plot
   i.e. Carbon stock for a sample plot= AG wood biomass + AG non woody biomass+ Litter + Soil carbon + Below ground Biomass
9. Upscale the results to the stratum

Forest carbon accounting is a multi-disciplinary task. It requires expertise from forestry science, ecological modeling, statistics, remote sensing, and at the field measurement level. The capacity to undertake forest carbon accounting is geographically diverse and building this capacity is essential. Good and complete information on the sources and sinks of carbon is a pre-requisite for appropriate emission targets and goals. Greater investment in forest carbon accounting is required, not only research to improve and standardize methods but also at a more local level to improve data sets.

Forest carbon accounting can be divided into three forms.
Stock accounting assesses the magnitude of carbon stored in forest ecosystems at a single point in time. This often forms a starting point for emissions and project-level accounting.
This is the practice of establishing the terrestrial carbon stock of a territory and average carbon stocks for particular land uses. Stock accounting allows carbon-dense areas to be prioritized in regional land use planning.

Emissions accounting assesses the net greenhouse gas emissions to the atmosphere resulting from forests. It is used to quantify the exchange of GHGs between the atmosphere, terrestrial vegetation and soils through photosynthesis, respiration, decomposition and combustion.
There are two main approaches to emissions accounting and both approaches are supported under IPCC guidance (IPCC, 2003).

- the inventory approach and
- the activity-based approach

The inventory approach utilizes two forest carbon stock accounting assessments at different time periods. It is also called periodic accounting, or the stock-difference approach.

Equation 1: Inventory/Periodic Accounting

- $\Delta C = \Sigma (Ct_2 – Ct_1) / (t_2 – t_1)$
    - ΔC = carbon stock change, tonnes C per year
    - Ct_1 = carbon stock at time t1, tonnes C
    - Ct_2 = carbon stock at time t2, tonnes C

The activity-based approach estimates carbon stock change by multiplying the area of land-use change by the impact of the change. Using the activity approach requires understanding of the rates of carbon gain and loss, commonly expressed as average biomass increments, for growth, and emissions factors for biomass losses, due to harvesting of wood products and disturbances. The activity-based approach estimates the net balance of additions to and removals from a carbon pool. The activity-based approach, also called the gain-loss or flux approach, estimates changes in carbon stocks by first establishing the rate of area change in land use and multiplying this by the response of carbon stocks under a particular land use. This assumes that the biological response of a given land use is based indirectly on rates of carbon losses and gains by an area or it is directly measured with the aid of technology.

Where the gains and losses in carbon stock can be given as a standard rate of emissions per unit activity, an emissions factor replaces (C1 – C2) in Equation 2. The activity-based approach is useful where individual carbon pools are difficult to measure and is less susceptible to short-term variation in carbon stocks.

This approach requires understanding of the rates of carbon gain and loss expressed as average biomass increments, for growth, and emissions factors for biomass losses.

- **Equation 2: Activity-based/Flux Accounting**
    - $\Delta C = \Sigma [A * (C_I – C_L)]$
        - A = area of land, ha
        - CI = rate of gain of carbon, tonnes C per ha per year
        - CL = rate of loss of carbon, tonnes C per ha per year

Emission reductions accounting assesses the decrease in emissions from project or policy activities, often so that they can be traded. Accounting for emission reductions requires an understanding of a number of supplementary principles:

- the complexities of baseline establishment,
- demonstration of additionality,
- issues of leakage, and
- the permanence of emissions reductions.

3.3. The Tiers

The IPCC Good practice Guide (GPG) and Agriculture, Forestry and Other Land Use (AFOLU) guidelines present three general approaches for estimating emissions/removal of greenhouse gases, called "Tiers" ranging from 1 to 3, representing increasing level of data requirement and analytical complexity. Despite differences in approach among the three Tiers, all tiers have common adherence to IPCC good practice concepts of *transparency, completeness, consistency, comparability* and *accuracy*.

Tier 1 requires no new data collection to generate estimates of forest biomass. Default values of forest biomass and forest mean annual increment are obtained from the IPCC emission factor database. Its estimation thus provides limited resolution of how forest biomass varies sub-nationally and has a large error range for growing stock in developing countries. Tier 1 has essentially no data collection needs beyond consulting the IPCC table and Emission Factor Data Base (EFDB), corresponding to broad continental forest types (e.g. African Tropical Rainforest).

Tier 2 is akin to tier 1 in that it employs static forest biomass information, but also improves on that approach by using country specific data (i.e. collected within the national boundary), and by resolving forest biomass at finer scales through the delineation of more detailed strata

Tier 3 is the most rigorous approach associated with high level of effort and sophistication. It uses actual inventories with repeated measurements of permanent plots to directly measure changes in forest biomass and/or uses well parameterized models in combination with plot data. Tier 3 often focuses on measurements of trees only, and uses region/forest specific default data and modeling for the other pools. The tier 3 approach requires long term commitments of resources and personnel, generally involving the establishment of a permanent organization to house the program. It is expensive in the developing countries context. Unlike tier 1, tier 3 doesn't assume immediate emissions from deforestation. Tier 3 requires mobilization of resources where no national forest inventory is in place (i.e. most developing countries).

The tiers should be selected on the basis of goal, cost, and significance of the target source/sink, available data and analytical capability. If Tiers 1 or 2 is used both for the reference period and for future monitoring of emissions from deforestation and degradation, the error margin may be so great that the amount of emissions to be claimed and traded could be small make the effort not worthwhile. The IPCC recommends that it is good practice to use higher tiers for measurement of significant sources/sinks.

4. The Concepts of Baseline, additionality, leakages and Permanence

4.1. Baselines

In order to set emission reduction targets, a baseline scenario must be developed. A baseline scenario estimates what would have happened in the absence of a policy or project. It is required so that the mitigation impact of a project or policy can be quantified. It is used as a reference case for quantifying mitigation performance.
Baseline establishment requires understanding:

- the drivers of land use change like agricultural expansion, wood extraction and expansion of infrastructure.
- The underlying driving forces: demographic, economic, technological, policy / institutional, and cultural / socio-political factors.

Three approaches for baseline establishment

1. extrapolating existing or historical rates of deforestation -also called business-as-usual;
    - Historic emissions: based on historical deforestation rates

- countries with historically high rates of deforestation will be rewarded more

2. Estimating changes in carbon stocks from land uses that represents economically attractive courses of action.
   - Historic deforestation + adjustment factor: to include recent development (deforestation)

3. Estimating changes in carbon stocks from the most likely land use at the time the project starts. Future projections: using modeling

4.2. Additionality

Additionality refers to carbon emission reductions that are additional to what would have occurred without the REDD+ project. In order to be additional, the project must demonstrate that it would have not happened in the absence of carbon finance. The following figure shows the concepts of baseline and additionality.

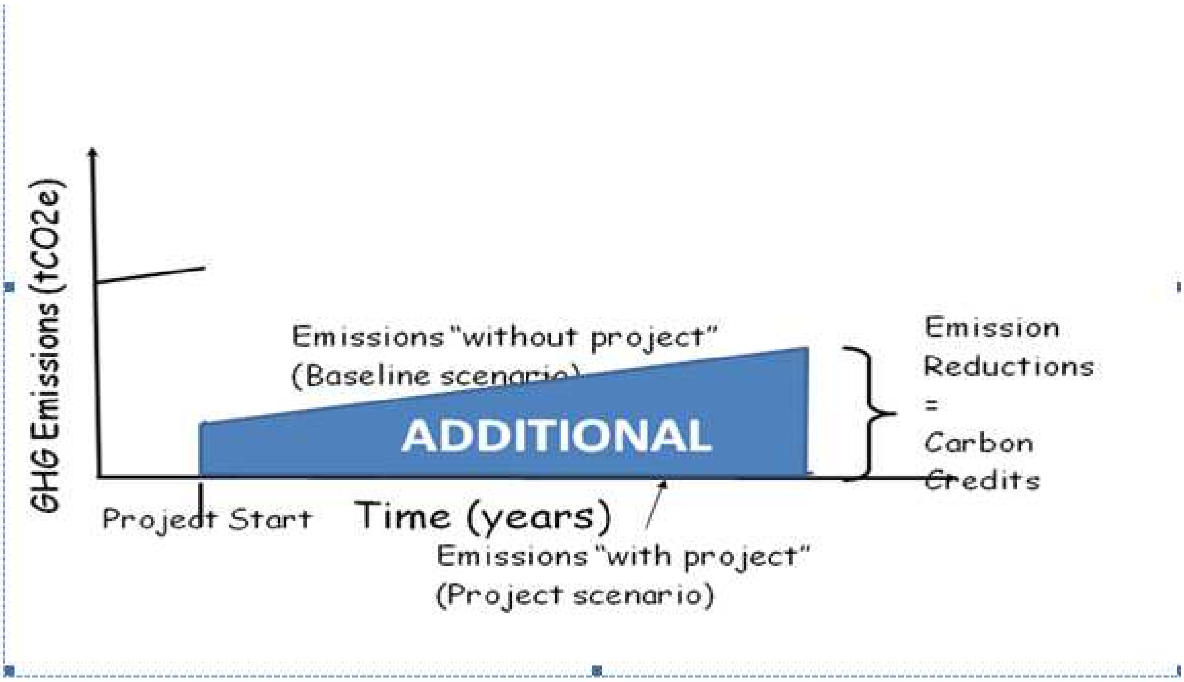


Figure 7: Reference levels

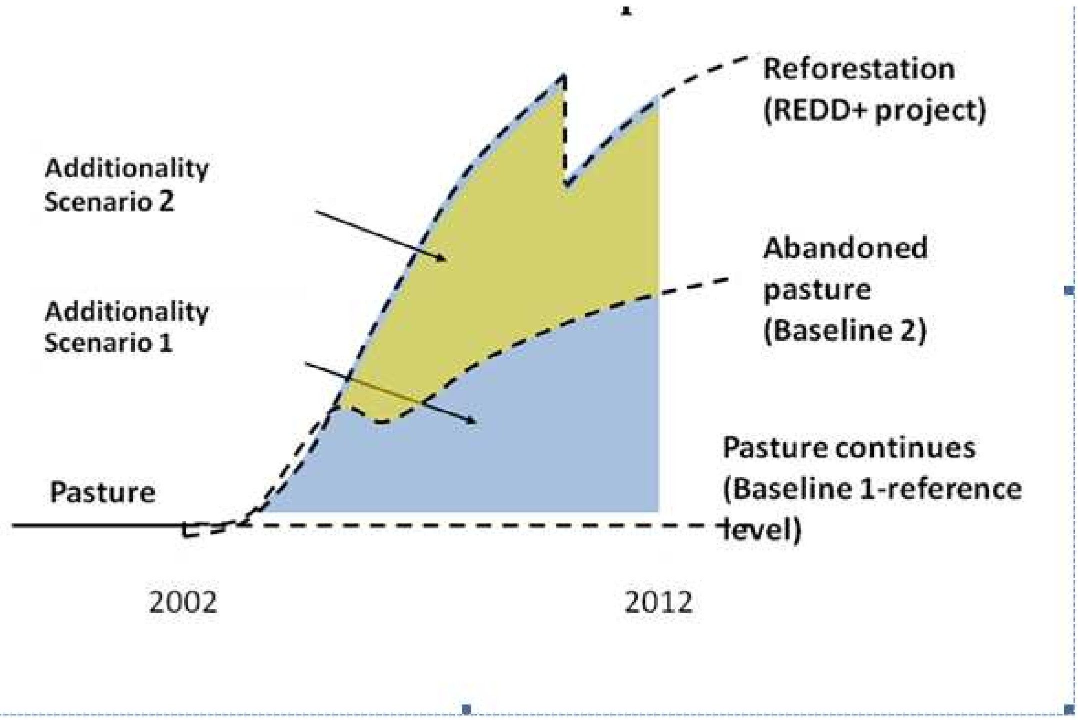


Figure 8: An example: reforestation of an abandoned pasture

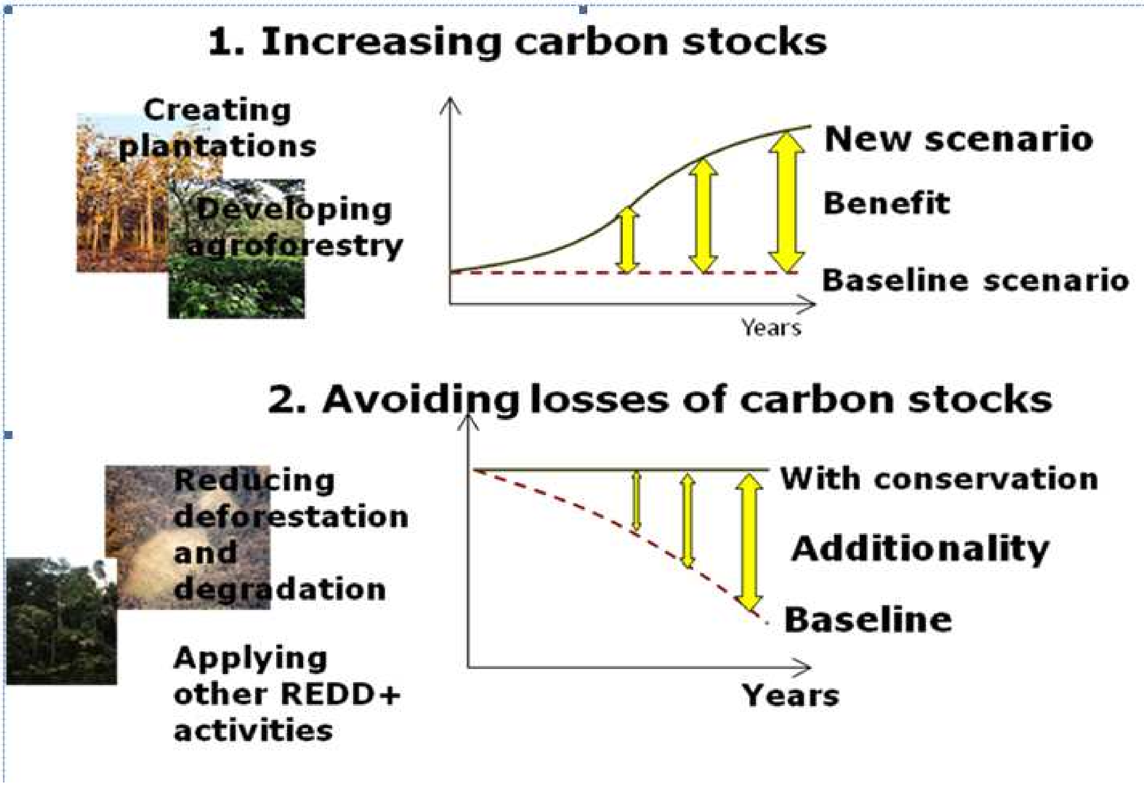


Figure 9: Scenarios for increasing carbon stocks and avoiding losses of carbon stocks

4.3. Leakages

Leakage is a process by which emissions are reduced in one area but are also impacted outside of the area in question. This literally means transfer of forest use from one forest to other forests because emissions are merely shifted to another geographical area. A carbon project must identify and determine the extent of all forest utilization levels before the start of the project and make sure that the uses are not transferred elsewhere in the presence of the project.

Therefore, leakage is what occurs when a reduction of emissions in one area leads to an increase in emissions in another area. For example, a REDD project that protects forest in one area, but leads to increased deforestation activities elsewhere. Leakage is also known as emission displacement. Leakage can be reduced by adjusting carbon projects for leakage discounting. Establishment of leakage zone around the core REDD activity areas is one of the methods to deal with leakage.

Adequate assessments of leakage include socio-economic surveys, remote sensing and assessment of market effects.

4.4. Permanence

Permanence refers to the persistence of emission reductions over time. Forest carbon sinks, having delivered emissions reductions, may deteriorate or be depleted over the long term. This could be a result of natural disturbances including fire, pests and disease, or anthropogenic disturbances such as poor management and political instability leading to land-use change. Therefore, the temporary Certified Emission Reductions (tCERs) may expire at the end of the commitment period and must be verified every five years. After verification, a tCER can either be re-issued (if the sequestered carbon remains intact). This means that the designer of carbon project should ensure that the benefits realized by the project are sustainable with minimal risks in the event of fire, drought and change in government policy to ensure the sustainability of the project.

The issue of permanence will focus on the reversibility of reduced greenhouse gas emissions. Mechanism to deal with permanence risk include buffer- a non-tradable reserve of emission reduction which are set aside and not sold.

SECTION-II: FOREST CARBON STOCK ASSESSMENT

1. Forest Management under REED+

Under UNFCCC, countries are negotiating REDD (reducing emissions from deforestation and forest degradation in developing countries) as an instrument that would provide incentives to developing countries to carry out forest-based climate change mitigation actions. Many countries support an instrument that provide incentives for essentially all land-based forest mitigation measures, referred to as "REDD+"; this includes reducing emissions through reducing deforestation and forest degradation, forest conservation, sustainable management of forests and enhancement of forest carbon stocks.

Thus far, REDD+ negotiations and national preparations have mainly focused on defining transparent monitoring, reporting and verification (MRV) systems, and on forest governance and national policies and strategies for REDD+. While these are key pillars for REDD+ construction, improving forest management practices will also be of fundamental importance to reach the desired objective of curbing emissions from deforestation and forest degradation and to conserve and enhance forest carbon stocks on the ground. Forest management will be fundamental to the successful implementation of national REDD+ strategies.

Forests can be net sinks or net sources of carbon, depending on their age, health and susceptibility to wildfires and other disturbances, as well as on how they are managed. Forest management interventions that result in carbon emission reductions or increased carbon sequestration could potentially be rewarded by REDD+.

While most sustainable forest management projects may have a positive impact on climate change mitigation and adaptation, only some forest ecosystems have high potential for REDD+, when the opportunity costs of other alternative land uses, the main drivers of deforestation and degradation, the additionality of REDD+ and the tenure issues and institutional framework are taken into account. Sustainable forest management must also be promoted and supported for forest ecosystems with low potential to benefit from REDD+ incentives, as they may still have important environmental, economic and social functions. REDD+ is a financial mechanism of the UNFCCC, which would provide developing countries with incentives to reduce carbon emissions from forests. The major climate change mitigation strategies under REDD+ includes:

- Enhancement of carbon stocks (through afforestation and regeneration)
- Sustainable forest management
- Avoided degradation
- Avoided deforestation
- Conservation of carbon stocks

The REDD+ schemes allow forest conservation to compete on economic terms with the drivers of deforestation such as conversion to arable land, pasture field for livestock and other forms of land use. Current economic drivers favor destructive logging practices and conversion of forest to other land use systems. Under REDD+, countries that are able to effectively reduce their carbon losses from deforestation and degradation compared to a reference scenario through conservation, sustainable forest management, and enhancement of forests carbon stock will be able to claim and sell the corresponding carbon credit internationally.

Credits from reduced emissions, would be quantified and that positive quantity would then become a credit (Certified Emissions Reductions) that could be sold in an international carbon market. Alternatively the credit could be handed to an international fund set up to provide financial compensation to participating countries that conserve their forest. All the five activities of the REDD+ aim to reduce emissions from deforestation and forest degradation in developing countries. To place a value on the carbon-bearing potential of any forested area, we must accurately estimate how much carbon is being stored, and how much has been conserved through REDD+ project implementation activities.

2. Roles of Forest and Soil in Climate Change Mitigation

It is known that 45% of the earth's terrestrial carbon is stored in forests, in 2005, forests covered 4 billion ha of the earth's surface (30%), of this, African forests covered 635 million and accounted for around 16% of the world's forests (Pearson, et al, 2005).

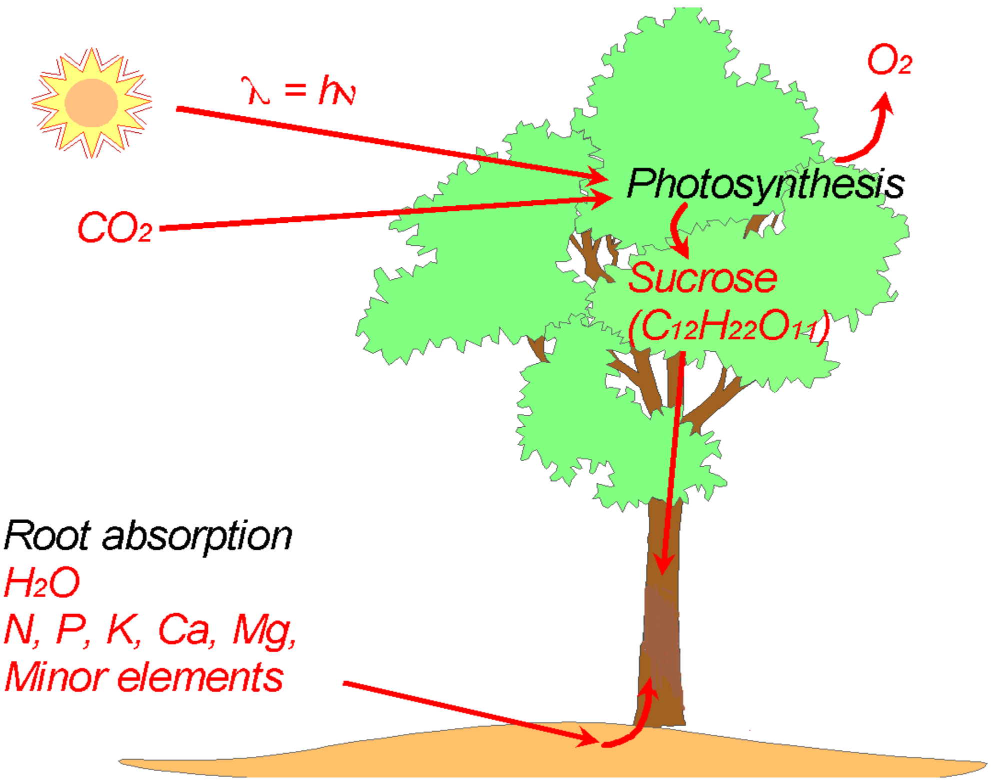


Figure 10: An illustration of the mechanism of carbon sequestration

Forests are therefore both sources and sinks of carbon. They are sources when they release carbon stored in their biomass to the atmosphere through deforestation and degradation, and they sink carbon from the atmosphere through photosynthesis and store it as biomass as they grow. Globally forests are net sinks, thus, they absorb more carbon out of the atmosphere than they emit. However, of the 2.6 billion tons of carbon that forests annually absorb, 60% is emitted back into the atmosphere through deforestation. Emission from deforestation and degradation accounts for 17% of the Global GHG volume, nonetheless, deforestation is the second most important human induced source of CO_2 to the atmosphere after fossil fuel combustion. In addition to regulating climate change, forests provide a number of important services such as regulation of water flow, reduction of runoff, erosion, siltation, flooding, and provide direct goods like food, medicine and fuel wood. These are collectively called **Ecosystem goods and services** of forests.

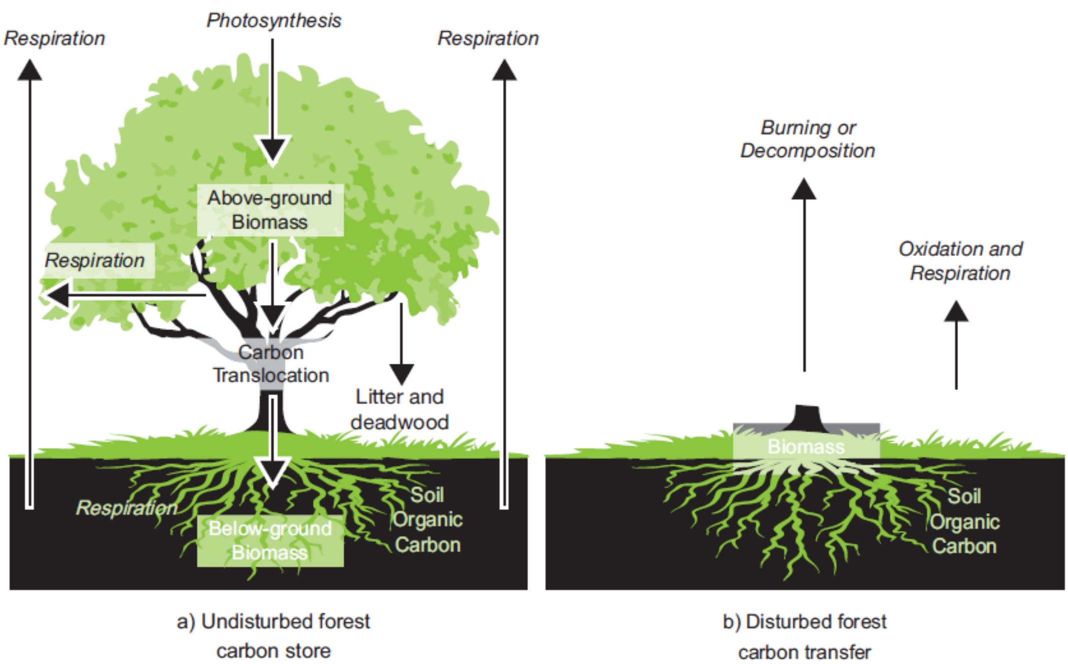


Figure 11: Demonstration of carbon storage and emission under two scenarios

(Source: Malhi et al., 1999)

Soils also sink carbon and release to the atmosphere when the equilibrium (i.e. inflow and outflow) carbon content is disrupted due to human actions such as land use change, precipitation, temperature, etc. During this process, soil may act as a carbon source or a carbon sink according to the ratios between inflows and outflows.

3. Methods for Estimating Carbon Emissions from Deforestation and Degradation

A range of forest management and conservation practices can reduce or abate emissions and/or sequester carbon. Many of these activities, however, may be impracticable for an emission trading program because they might not meet credible standards for quantifying, monitoring, and verifying emission reduction or carbon storage. Accessing carbon finances through REDD+ requires, among other things, measurements of carbon stock changes in forests.

The IPCC Good practice Guide (GPG) and Agriculture, Forestry and Other Land Use (AFOLU) guidelines present three general approaches for estimating emissions/removal of greenhouse gases, called "Tiers" ranging from 1 to 3, representing increasing level of data requirement and analytical complexity. Despite differences in approach among the three Tiers, all tiers have common adherence to IPCC good practice concepts of *transparency, completeness, consistency, comparability* and *accuracy.*

Tier 1 requires no new data collection to generate estimates of forest biomass. Default values of forest biomass and forest mean annual increment are obtained from the IPCC emission factor database. Its estimation thus provides limited resolution of how forest biomass varies sub-nationally and has a large error range for growing stock in developing countries. Tier 1 has essentially no data collection needs beyond consulting the IPCC table and Emission Factor Data Base (EFDB), corresponding to broad continental forest types (e.g. African Tropical Rainforest).

Tier 2 is akin to tier 1 in that it employs static forest biomass information, but also improves on that approach by using country specific data (i.e. collected within the national boundary), and by resolving forest biomass at finer scales through the delineation of more detailed strata

Tier 3 is the most rigorous approach associated with high level of effort and sophistication. It uses actual inventories with repeated measurements of permanent plots to directly measure changes in forest biomass and/or uses well parameterized models in combination with plot data. Tier 3 often focuses on measurements of trees only, and uses region/forest specific default data and modeling for the other pools. The tier 3 approach requires long term commitments of resources and personnel, generally involving the establishment of a permanent organization to house the program. It is expensive in the developing countries context. Unlike tier 1, tier 3 doesn't assume immediate emissions from deforestation. Tier 3 requires mobilization of resources where no national forest inventory is in place (i.e. most developing countries).

The tiers should be selected on the basis of goal, cost, and significance of the target source/sink, available data and analytical capability. If Tiers 1 or 2 is used both for the reference period and for future monitoring of emissions from deforestation and degradation, the error margin may be so great that the amount of emissions to be claimed and traded could be small make the effort not worthwhile. The IPCC recommends that it is good practice to use higher tiers for measurement of significant sources/sinks.

During COP-15 at Copenhagen, Denmark, developing country parties were requested among other things to establish a national or sub-national forest monitoring system that uses a combination of remote sensing and ground-based forest carbon inventory approaches (Tier-3) for estimating, as appropriate as possible, anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks, forest carbon stocks and forest area changes. Different tiers can be applied to different pools where they have a lower importance. For example, where primary observations demonstrate that emissions from the litter or dead wood or soil carbon pool constitute less than 25% of the emissions from deforestation, the tier 1 approach using default transfers and decomposition rates would be justified for application to that pool.

4. Key Steps in On-site Forest Carbon Stock Assessment

A hybrid approach (Tier-3) involving a combination of approaches (e.g., combining modeling with on-site sampling and independent verification) is preferable in terms of improved accuracy of carbon stock estimation. The on-site forest carbon stock assessment involves the following key steps:

4.1 Definition and Demarcation of Project Boundary and Mapping

The REDD+ project proponent, with active participation of relevant stakeholders including communities living in and around the project area, should delineate the project boundary before proceeding to the next steps. This process enables one to know the actual size of the project and is crucial for the sustainability of the carbon stock. When the boundary is agreed among stakeholders, coordinates should be recorded using Global Positioning System (GPS). The GPS data will be later transferred into computer in order to draw the base map of the project and estimate the area using Arc GIS software. The Arc GIS software would be used to distribute and locate sample plots on the base map. The software also generates coordinates of each sample plot, which is later used to locate the plots on the ground during the actual carbon stock assessment.

4.2 Stratification of the Project Area

Stratification refers to the division of any heterogeneous landscape into distinct sub-sections (strata) based on some common grouping factor. In order to facilitate fieldwork and increase the accuracy and precision of measuring and estimating carbon, it is useful to divide the project area into sub-populations or “strata” that form relatively homogenous units. Stratification is the critical step that will allow the association of a given area of deforestation and degradation with an appropriate vegetation carbon stock for the calculation of emissions. Stratifying an area by its carbon stocks can increase accuracy and precision and reduces costs. Stratification of a REDD+ project area to more or less homogenous forest units should be on the basis of parameters such as pressure on the forest, history of land use in the project area, the climate regime (rainfall and temperature), topography, socio-economic activities, etc.

The size and spatial distribution of the land area does not influence site stratification – whether one large contiguous block of land or many small parcels are considered the population of interest, they can be stratified in the same manner. The stratification should be carried out using criteria that are directly related to the variables to be measured and monitored – for example, the carbon pools in trees. If stratification leads to no, or minimal, change in costs, then it should not be undertaken. Potential criteria for stratification in Ethiopia could include:

- Elevation
- Rainfall regime
- Level of disturbance
- Slope

4.3 Decision on Forest Carbon Pool to be measured

The decision to include or exclude a pool in the carbon accounting scheme as part of REDD+ accounting scheme is governed by:

- Available financial resources,
- Availability of existing data,
- Ease and cost of measurement,
- The magnitude of potential change in the pool,
- Principles of conservativeness,
- Availability and accuracy of methods to quantify change and the cost to measure.

Above all is the principle of conservativeness. This principle ensures that reports of decreases in emission are not overstated. Cleary for this purpose, both time zero (baseline) and subsequent estimations must include exactly the same pools. For example if dead wood is omitted during first carbon stock assessment (i.e. baseline), it has to be also omitted during the second and subsequent carbon assessments.

For REDD+ projects, carbon in trees should be measured and be part of carbon accounting scheme at all times as this is where most of the carbon benefits will be derived from. On the other hand, measurement of carbon in the under-story is recommended in cases where this is a significant component, such as in agro-forests or open woodlands or coffee farms. Only pools that are measured (or estimated from a measured parameter) and monitored are incorporated into the calculation of carbon benefits.

4.4 Determination of the Type of Sample Plots

Permanent sample spots generally are more efficient in estimating changes than temporary/point plots because it is easier to distinguish actual trends from differences that are only due to changed plot selection. Permanent sampling plots are regarded as, statistically more efficient in estimating changes in forest carbon stocks than temporary plots, because there is high covariance between observations at successive sampling events. Moreover, permanent plots permit efficient verification, if needed, at relatively low cost: a verifying organization can find and measure permanent plots at random to verify, in quantitative terms, the design and implementation of the carbon monitoring plan.

However there are also some risks in the use of permanent sample plots. If the locations of permanent sample plots are known to land managers (e.g., by visibly marking the plots), there is a risk that management of the permanent plots will differ from the management of the other areas. If this occurs, the plots will no longer be representative and there is an obvious risk that the results will be biased. If it is perceived that there might be a risk of the above situation, it is good practice to assess some temporary plots as a control sample in order to determine if the conditions on these plots deviate from the conditions of the permanent plots. Where measurements are only made at one point in time – such as for baseline estimations – there is no value in marking plots and trees. For ongoing carbon monitoring, permanent sample plots are generally considered as the statistically superior and cost- and time-efficient means for evaluating changes in carbon stocks.

4.5 Decision on the Shape and Size of the Sample plot

The size and shape of the sample plots is a trade-off between accuracy, precision, time and cost for measurement. There are two types of plots – single plots of a fixed size or nested plots containing smaller sub-units of various shapes and sizes. Nested plots are a practical design for sampling for recording discrete size classes of stems. They are well-suited to stands with a wide range of tree diameters or to stands with changing diameters and stem densities. Single plots may be preferred for systems with low variability, such as single species plantations. Experience has shown that nested plots can be the most cost-efficient.

Nested plots are composed of several sub-plots (typically two to four, depending upon forest structure), each of which should be viewed as separate. The plots can take the form of nested circles, square or rectangles. Circles work well if you have access to distance measuring equipment ([DME], for example, from Haglof, Sweden) because then the actual boundary around the plot need not be marked. If DME is not available, it may be more efficient to use rectangular plots that are laid out with tape measures and stakes. The square and rectangular plots are also preferred as they tend to include more of the within-plot heterogeneity, and thus be more representative than circular plots of the same area.

The design of nested quadrates of different sizes (Figures 4 and 5 below) obeys requirements for measuring and counting vegetation of different sizes and strata, and for collecting debris and litter for estimation of biomass. The 1m X 1m quadrate is used to collect litter, herbs (live above ground non-woody with DBH < 2 cm) and soil samples. The 10m X 10m quadrate is used for sampling above ground live trees with 2-10 cm DBH (shrubs) and dead wood. Trees with DBH ≥ 50 cm should be counted in the entire sample plots. The size and number of nested quadrates can vary depending on the homogeneity and heterogeneity of species in the strata (land cover classes).

Decision regarding the size, number and repetition of the nested plots can be made through a reconnaissance survey when the team is in the field.

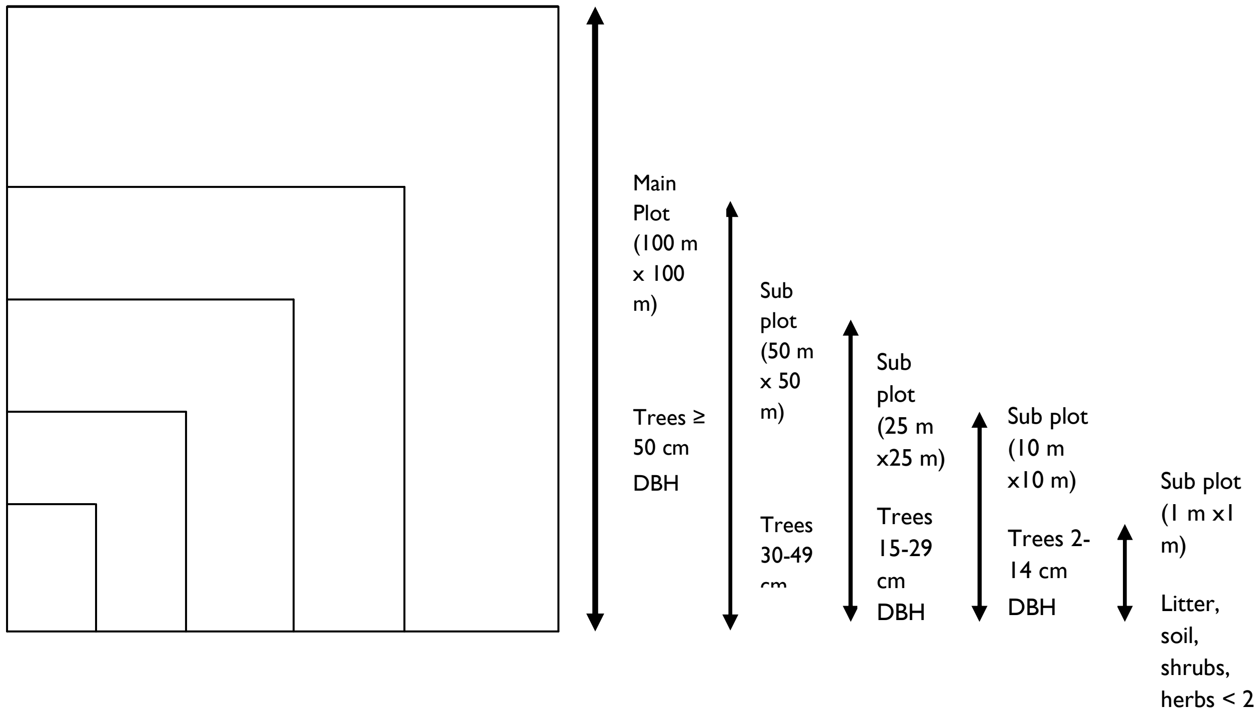


Figure 12: Nested plot design for sampling of various carbon pools in Heterogeneous Stratum

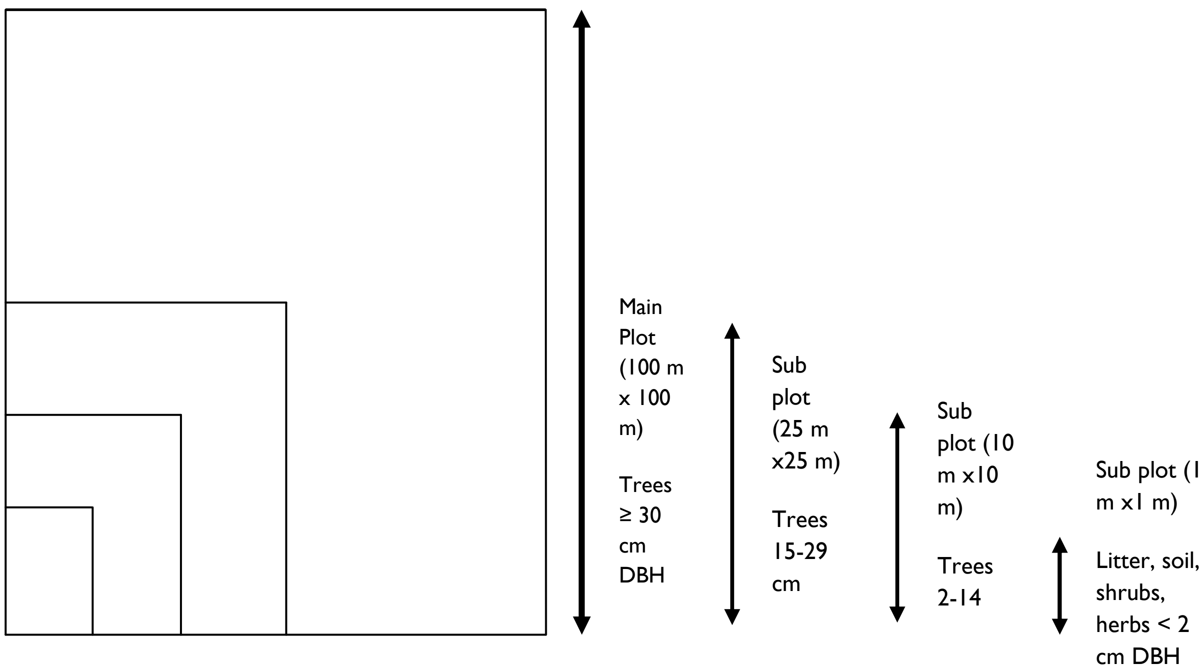


Figure 13: Nested Plot design for sampling of various carbon pools in Homogeneous Stratum

It, however, should coincide with recommended practice in the ecological literature and represent a compromise between recommended practice, accuracy and practical considerations of time and effort. Once decided, the dimension and number of the nested plots should be consistent in all sample plots in the strata.

4.6 Determination of Number of Sample Plots

Once the strata's are identified and agreed on, the type of plots and shapes are decided, the number of sample plots required in each stratum must be determined. The decision on the number of plots depends on vegetation type, logistics, accuracy level, manpower and cost. The number of samples for each stratum is selected proportional to its size.

But importantly, it is instructive to conduct the inventory with statistical rigor to ensure that the results can be used confidently to aid decision making and to draw inferences. To do this, it is important to first determine the number of plots that are required to attain the precision expected of the results. However, there is the need to satisfy specific data inputs to ensure that the acceptable number of plots has been generated. This activity constitutes part of an exploratory inventory which precedes the actual inventory.

1. Identify the desired precision level. Accurate levels of the inventory can be obtained from a precision of ± 10% at 96% confidence interval (CI).
2. Preliminary data of average carbon stocks of each stratum should be generated

$$\bar{x} = \frac{x_1 + x_2 + \ldots + x_n}{n} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad s^2 = \frac{\sum_{i=1}^{n}(X_i \quad \bar{X})^2}{n-1} \qquad s = \sqrt{s^2}$$

Average Variance

SD

3. Estimate standard deviation and variance from the preliminary data. Between 6-10 plots are enough to calculate the variance
4. Calculate the required number of plots

Once the variance for each land use system/legend, the desired level of precision and estimated error (referenced in the confidence level selected) are known, the number of sampling plots required can be calculated. The generic formulas for calculating the number of plots for different land systems are:

1) For one land use system.

$$n = \frac{\left(\sum_{h=1}^{L} N_h * s_h\right)^2}{\frac{N^2 * E^2}{t^2} + \left(\sum_{h=1}^{L} N_h * s_h^2\right)}$$

Where:

n = number of plots

E = allowed error (average precision x level selected).

As seen in the previous step, the recommended level of accuracy is ± 10% (0.1) of average but can be up to ± 20% (0.2).

t = statistical sample of the t distribution for a 95% level of confidence (usually used as sample number)

N = number of plots in the area of the layer (stratum area divided by the plot size in ha)

S = standard deviation of land use system

Source: http://www.winrock.org/ecosystems/tools.asp

Once the number of plots is calculated, a sampling grid could be used to systematically layout the sample plots on the vegetation map (aerial photos or topographic map) of the project. Each sample point represents an area corresponding to the size of the grid cell of the sample layout. For example, when sample points are selected from a square systematic grid with 1000 meters distance between the points, each sample point will represent an area of 1 km X 1 km= 10 ha. Thus, if 15 plots fall within specific stratum, the interest of the area estimate will be 15 X 10 ha= 150 ha. A sample plot of 100m X 100m will be laid at every stratum for forest carbon stock data collection. On the other, hand the size of the sample plot can be less than 100m by 100m when the stratum is homogeneous.

4.7 Determining Measurement Frequency

It is recommended that for carbon accumulation, the frequency of measurements should be defined in accordance with the rate of change of the carbon stock. Measurements of initial stocks employed in the baseline must take place within ± 5 years of the project start date, for simplicity referred to here as stocks at t=0. The estimates are valid in the baseline for 10 years, after which they must be re-estimated from new field measurements. The re-measured estimate should be within 90% confidence interval of the t=0 estimate (baseline), the t=0 stock estimate takes precedence and is re-employed, and where the re-measured estimate is outside (i.e. greater than or less than) the 90% confidence interval of the t=0 estimate, the new stock estimate takes precedence and is used for the subsequent period. Below are the general steps to be followed to conduct carbon stock assessment for the five forest carbon pools.

4.8 Preparation for field work and Logistic Requirements

4.8.1 Field Equipment

Prepare tools and equipment for the field work. The following are some of the tools and equipment required for the fieldwork.

Table 1: Equipment list for each inventory team

Equipment	Quantity	Equipment	Quantity
Aluminum nails (Aluminum Siding Plain Shank Style Aluminum Nails: 2-1/4" Long, 0.128" diameter shank, 3/8" diameter head. Approximately 333 nails per pound).	6 ponds	Sheet holder/clip boards	2
Aluminum numbered tags (rounded numbered aluminum tags: 1-100)	15 packs	GPS (Garmin Oregon 550)	1
Backpack	1	Hammers	3
Batteries (AA&9-volt)	50 pairs	Permanent marker pens	2 boxes
Stakes and machete	8 stakes 3 machetes	Plastic marking tags (for labeling plot centers)	10 pieces
First aid kit (forestry suppliers' loggers first-aid kit)	1 box	Plastic tarps (1 m^2)	2
Nylon ropes	5 (100 m long)	PVC pipe & caps	40 pieces
Compass (Suunto challenger MCA-D)	1	Data sheets	3 A4 rims
Cotton rags (for cleaning equipment)	1	Laser Hypsometer	1
DBH tapes or calipers (forestry suppliers metric fabric diameter tape: 160 cm)	5	Red paint and brush	10 litres
Fiberglass meter linear tapes (open reel 100 m fiberglass tape measure)	2	Stapler with pins	1 set
Field vests (reflective field vests)	6		
Flagging tape or ribbons	15 bundles		

4.8.2 Safety Procedures

Carbon stock assessment is a very intensive and time taking task that may require camping for some of the less accessible plots. It is therefore important to get prepared well in advance in terms of tools and equipment, Logistics, transports, clothing, boots, first aid kit, camping equipment, etc. it is important to be appropriately dressed in full attire and safety boots. Ideally colognes should be avoided since they attract bees.

4.8.3 Composition of the field team

A field team of 6-8 members (2 foresters, 1 botanist, 3 technical assistants, one of whom has experience in soil sampling and 2 people from the local) should be deployed. The team should divide roles among themselves. One of the most difficult tasks in practical fieldwork is the identification of the species on the ground. Therefore, the knowledge of local people who have been working and living in or near the forest should play an important role in data collection. Local people can identify species accurately using local or even botanical names.

In general, the team members should have prior experience and knowledge of forest inventory techniques. Prior training should be organized for team members who are not familiar with the conventional inventory techniques. It is also ideal to have a team member who is very conversant with the landscape, and can assist in the navigation of the team from one point to the other and also from and to the camping site.

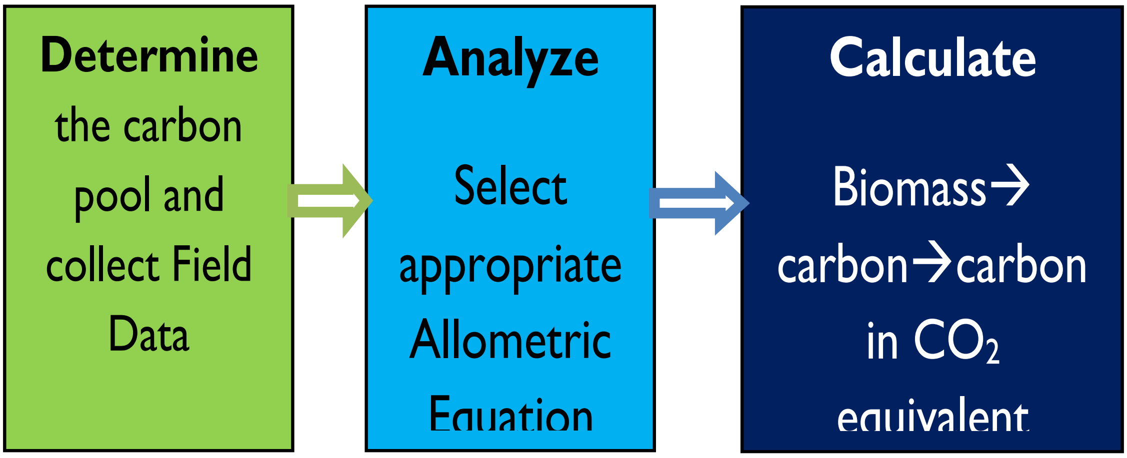
5. Conducting Carbon Stock Assessment

Carbon stock accounting is important to determine the carbon stock in the project baseline, to develop project idea note (PIN) and project design document (PDD), to validate, register and implement emission reduction measures. Once the sampling points are identified and all preparations are finalized, the task will be conducting carbon stock accounting in the field. Depending on the project requirements, some of the pools can be omitted, but in this manual, users shall be taken through specific steps in generating data for all the carbon pools.

Steps

10. Familiarize the field team with the field tools and equipment and provide training in advance
11. Locate the first sample plot 50 m into the forest from the edge of the forest
12. Take GPS reading at all corners including compass reading for permanent sample plots
13. Take correct compass reading to the next corner point of the sample plot. Use ranging poles for accurate compass reading to the corner point
14. Add or subtract 90 degree to/from the preceding reading to go to the next corner point
15. While measuring the distance between two corners, take the slope factor into account-use.
16. Lay the nested plots at two opposite corners of the principal plot
17. Collect data on all carbon pools (above ground -woody and non-woody, litter, soil and below ground) or for the carbon pools of your interest and label them
18. Calculate the biomass for each carbon pool
19. Calculate the aggregate carbon stock for the sample plot. i.e., Carbon stock for a sample plot= AG wood biomass + AG non woody biomass+ Litter + Soil carbon + Below ground Biomass

20. Upscale the results to the stratum



5.1 Estimation of Aboveground Carbon Stock

The above-ground biomass comprises all woody stems, branches, and leaves of living trees, creepers, climbers, and epiphytes as well as herbaceous undergrowth. For agricultural lands, this includes crop and weed biomass. To measure the biomass of vegetation which includes trees is not easy, especially in mixed, uneven-aged stands. It requires considerable labor and it is difficult to obtain an accurate measurement, given the variability of tree size distribution. The focus of this section will be on estimating carbon stocks of forests that are subject to deforestation and degradation. The mean carbon stock in aboveground tree biomass per unit area is estimated based on field measurements in fixed area sample plots or temporary sample points that are selected randomly or systematically

5.1.1. Aboveground Woody Vegetation

Assessment of aboveground tree biomass can be done non-destructively using allometric biomass regression equations. An estimate of the vegetation biomass can provide us with information about the nutrients and carbon stored in the vegetation as a whole, or the amount in specific fractions such as extractable wood.

To measure the biomass of trees is not easy, especially in mixed with uneven-aged stands. It requires considerable labor and it is difficult to obtain an accurate measurement given the variability of tree size distribution. It is hardly ever possible to measure all biomass on a sufficiently sample area by destructive sampling and some form of *allometry* is used to estimate the biomass of individual trees to an easily measured property such as its stem diameter.

For biomass estimation of woody vegetation any live plant greater than or equal to 2 cm DBH will be treated as above ground woody plant. Experience to date with the development of generic regression equations has shown that measurements of DBH explains more than 95% of the variation in tree biomass even in highly species rich tropical forests.

Steps

1. Measure the diameter of trees at breast height (DBH) or 1.3 meters or above the buttress of all trees that are above the minimum DBH (≥2 cm) in the sample plot or sub-sample plots. For multiple stems, measure all stems >10 cm diameter at 1.3 m. For multiple stems below 1.3 m, measure collar diameter. For coffee measure collar diameter (30 cm above the ground).
2. Make corrections for buttressed and grooved trees (this can be done subjectively)
3. If there are reasonable number of stranglers, Lianas and climbers, take DBH reading (Remember: avoid measuring a woody climber twice!)

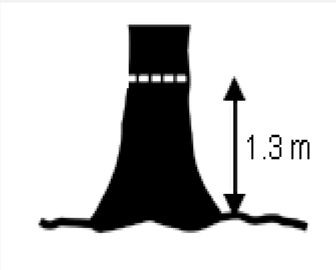
Measuring tree parameters

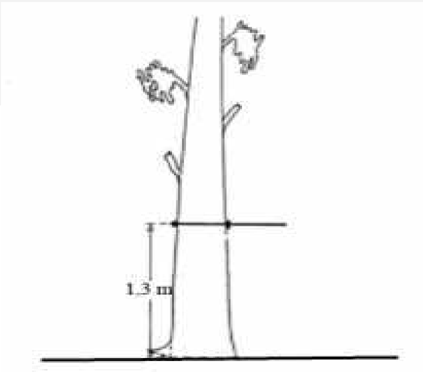
1. DBH measurement

In measuring the diameter of a tree, it is important to maintain a constant point of measurement. Ideally, for matured trees, diameter is measured at 1.3 m from the ground. However for saplings and coffee trees, the point of measurement should be 30 cm from the ground. Inaccuracies in measurement can result from vines entangled around the stem, slope, irregular trunk shape, including hollow trees, human error, as well as improper use of equipment.

In situations where one encounters an irregular shaped or hollow tree at the 1.3 m point, it is ideal to move further upwards to the relatively most cylindrical point. With stems entangled with vines, attempt must be made to pass the tape between the vine and the stem of the tree.

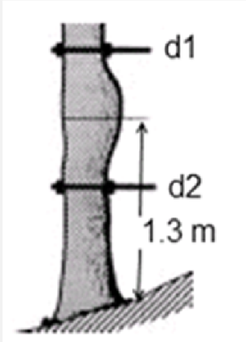
Breast height in flat terrain



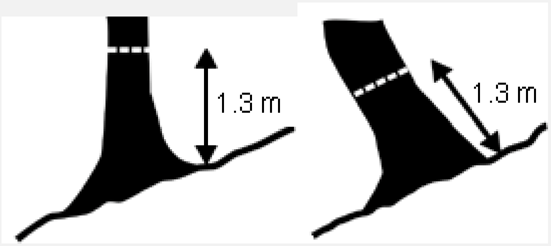


Non circular trees are to be measured in two *perpendicular diameters*

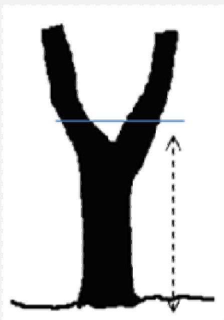
$$d = (d1 + d2)/2$$

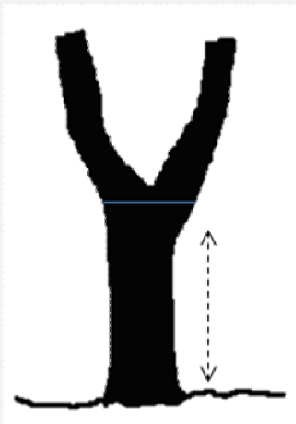


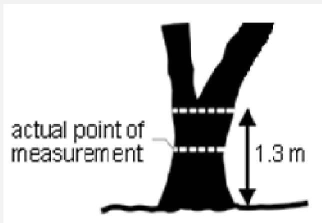
On inclined terrain *Dbh tree measurement at 1.3 m is taken from an uphill position*



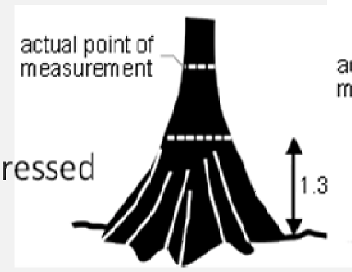
Fork tree

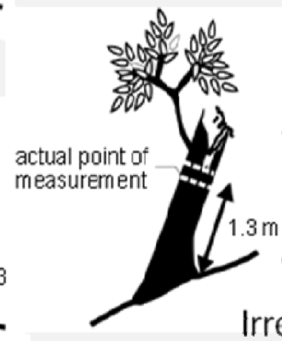


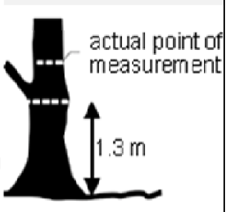




Buttressed







Irregular stem

2. Height Measurement

Tree height is a fundamental geometrical variable for trees. Unfortunately, most measures are based on visual inspection, and they are almost always considerably biased, as it is difficult to assess the size of vertical objects 10-40 m in height. One no-biased height estimate makes use of automated distance measurement tools, as reported here.

Tree height measurement

Tree height will be measured using a combination of a laser rangefinder and a clinometer. The supplied laser rangefinder (Nikon Laser 600, figure 1) takes measurements in yards or in meters, from 10 m to about 100 m, by increments of 0.5 m. (Note 1 yard = 0.9144 m). It is water-resistant, but not water-proof, so don't use it in the rain (you won't see tree tops anyway). The Nikon Laser 600 comes with one CR2 Lithium battery. Over 6,000 measurements can be achieved with just one battery. Do not throw it away when used. Store the equipment in a dry place overnight and when not used (in silica gel). Please read the notice carefully. The small button, when used together with the large button allows to convert from yard to meters. ALWAYS MAKE MEASUREMENTS IN METERS!! If you really can't figure out how to do it, be very clear that the measurement has been taken in yards on the field spreadsheet.

Figure 13: Laser rangefinder (Left) and height meter (right

The second piece of equipment is an optical height meter. It includes a clear notice. From distances of 15 m or 20 m, read off the instrument the height from the horizon to the tree base, then from the horizon to the tree top.

Two strategies can be followed for measuring tree heights.

(1) Recommended option. Find a spot where you have a clear view of the tree stem at around 15 m (for understory and mid-story trees), and 20 m (for canopy trees). Measure the precise horizontal distance from you to the stem using the rangefinder, L. Choose one scale in the height meter. Let us first assume that you will use the left scale (exact for a distance of 20 m). Estimate the position of the tree top, take a sighting of it through the height meter, and read the measure H1' on the left scale. Then, take a sighting of the tree base, and read the measure H2' on the left scale. The height measurement is

$H = (H1'+H2')*L/20$

Where all distance is expressed in meters. If you choose to use the central scale, then the following formula should be used:

$H = (H1'+H2')*L/15$

The rightmost scale of the height meter just provides the slope of the angle (in %). You don't need to report it. These formulas above are useful in rainforests, where it is sometimes difficult to find the right measurement spot exactly at 15 or at 20 m. Here the rangefinder is only used to find L. This technique should work well for most understory and mid-canopy trees. It could even work very well for canopy trees in newly formed gaps.

(2) For a number of canopy trees, however, tree height measurement is difficult because it is hard to see the upper crown. Field workers may then want to use directly the rangefinder from nearby the tree and shoot to laser beam to the upper branches or to the upper leaves. This would be a safe test to cross-check some of the measurements taken with method (1). However, only trees > 10 m in height can be measured this way. Also, you should shoot at approximately 90° to avoid overestimating the tree height (note also that you should add the height from your height to the ground, usually 1,60 m). The total height is simply; H1+H2.

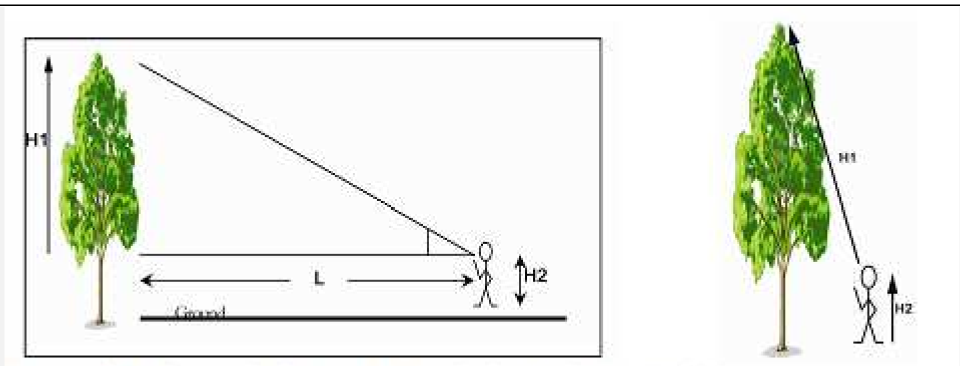


Figure 2. Left: Method 1 (recommended). Right: Method 2.

You should measure the tree heights within the Forest Dynamics Plot, to avoid the extra trouble of identifying trees. On the field spreadsheet, please record:

(a) Tree tag number

(b) Method of measurement (1 or 2)

(c) Exact distance from the tree L in meters (distances of 10 m or less should be reserved for small trees, distance of 30 m or more, to tall emergents).

(d) Exact height H1' read off the height meter (for method 1) or H1 read off the laser range finder (for method 2)

(e) Either exact measurement of H2' for method 1 if the terrain is not flat, or no measurement at all (meaning default height)

Do not forget to record the name of the field worker and his/her height on the spreadsheet, as it is useful in the subsequent calculations.

Steps

4. Measure the diameter of trees at breast height (DBH) or 1.3 meters or above the buttress of all trees that are above the minimum DBH (≥2 cm) in the sample plot or sub-sample plots. For multiple stems, measure all stems >10 cm diameter

at 1.3 m. For multiple stems below 1.3 m, measure collar diameter. For coffee measure collar diameter (30 cm above the ground).

5. Make corrections for buttressed and grooved trees (this can be done subjectively)
6. If there are reasonable number of stranglers, Lianas and climbers, take DBH reading (Remember: avoid measuring a woody climber twice!)
7. Measure height of dominant canopy trees (up to 15 trees) and establish diameter-height Regression equation. During biomass calculation, use this equation to obtain the height of all sampled trees.
8. Select or develop appropriate and valid allometric equation for forest type or group of species or each species or family. Examine the outputs of the allometric equation for under or overestimated biomass. If there is a serious problem of under or overestimation, look for alternative allometric equation. If there are two allometric equations from the same author for the same agro-ecology and parameter, use the recent equation.
9. Estimate above ground biomass for each tree (kg/tree) using the appropriate allometric equation[1];
10. Calculate the carbon stock of individual trees

$$Carbon\ stock\ per\ tree = \frac{\textbf{Biomass of the tree}}{2}$$

11. Calculate the carbon stock in a **sub-plot**

$$Carbon\ stock\ in\ sub\ plot = \ Summation\ of\ carbon\ stock\ of\ trees\ in\ the\ subplot$$

12. Estimate carbon stock for the **principal sample plot** (10,000 m^2)

$$Carbon\ stock\ of\ the\ prinicipal\ sample\ plot = \frac{Summation\ of\ carbon\ stock\ of\ sub\ plots}{areas\ of\ the\ sub\ plots} * 10{,}000\ m2$$

[1] See annexes 3 and 4 for general and species specific allometric equations for different agro-ecologies

13. Calculate the carbon stock in ton per hectare

$$Carbon\ stock\ of\ the\ smaple\ plot\ \left(\frac{ton}{ha}\right) = \frac{Carbon\ stock\ of\ the\ principal\ sample\ plot}{1000}$$

14. Calculate the mean above ground carbon stock of the plot in carbon dioxide equivalent

AG carbon stock in CO_2 equivalent (i.e. ton CO_2 equivalent) = Carbon stock in ton/ha * 44/12

5.1.2 Aboveground Non-Woody Vegetation.

Any live vegetation (woody and herbaceous) below 2 cm DBH will be considered as non-woody above ground biomass. The Sampling frame method (i.e. 1 m by 1 m frame) will be deployed to measure these non-woody vegetation. The frame will be laid at the four corners and the center of the sample plot

Steps

1. Lay the 1 by 1m frame at one of the four corners of the sample plot
2. Cut all living vegetation inside the frame at base and record the fresh weight
3. Take adequate sub-sample from the weighted sample and record the fresh mass of the sub sample. Repeat the same in the remaining corners and at the center
4. Label[2] the sub-sample and take them to laboratory and oven dry them at 70-80 0c temperature to constant weight
5. Estimate the dry mass of the original sample from the wet to dry ratio of the sub-sample

[2]Labeling above ground non-woody sample

$$\textbf{Dry mass of the sample} = \frac{\textit{Sub sample dry mass}}{\textit{Sub sample fresh mass}} * \textit{Fresh Mass of the sample}$$

6. Estimate the mean above ground non-woody dry mass for the sample plot

$$\textbf{Mean above ground non} - \textbf{woody Dry mass per plot} = \frac{DM1 + DM2 + DM3 + DM4 + DM5}{5\ (Or\ \#\ of\ sub - samples)} + 10{,}000m2$$

7. Estimate the mean above ground non-woody carbon stock for the sample plot

5.2. Aboveground Dead Trees

Dead trees could be either standing or down. Measurement method varies depending on the category and position of the dead wood

a) Standing Dead Tree

There are three categories of standing dead trees.

Category 1- with branches, twigs, big branches but no leaves

Category 2- with big branches alone

Category 3- only the bole

i) Measuring standing dead wood category 1 and 2

Steps

1. Apply nested sub plots similar to live trees
2. Identify the category of the standing dead wood
3. Measure two diameters i.e. at DBH and diameter at the top using a relascope that measures diameter. If there is no relascope, estimate the diameter at the top.
4. Measure the height using the laser hepsometer- don't forget to add your height at eye level to the hepsometer reading
5. Measure the height from closer distance
6. If there is a hole, measure the diameter of the hole, calculate the volume and subtract from the volume of the wood

7. To calculate the biomass, apply the allometric equation of live tree of similar species (or related species). Deduct 2-3% for leaves correction

ii) Measuring standing dead wood category 3

Steps

1. Measure the height
2. Measure DBH and top diameter
3. Cut a disk from fallen dead wood of similar or closer species.
4. Measure the mass of the disk
5. Measure the volume of the disk using **flotation method.** Cover the disk with plastic rubber to avoid water absorption. If you have density of the tree species, there is no need to calculate
6. Calculate the density of the disk

$$density = \frac{Mass}{volume}$$

7. Calculate the volume of the Bole

$$volume = \pi \frac{(d1^2 + d2^2) * height}{8}$$

8. Then calculate the dry mass of the standing dead wood from the density of the disk and volume of the standing wood
9. . Dry mass= density of the disk * volume of the standing dead wood

   NB: Half of the dry mass is the carbon stock

b) Down/laying Dead Wood

Can be assessed using either the line or the subplot method. The subplot methods is the most commonly used method. There are three categories of down woods based on density state. A ‘machete test’ could be applied to identify the category

There are three categories of categories of Dead Wood

1. **Category 1**- when the tree is hit by a matchet and produces **sound**
2. **Category 2**- when the tree is hit and the matchet slightly enters it is called intermediate
3. **Category 3**- when the dead lying wood is crumbles in to pieces due to the matchet hit

Spot method will be used for measuring fallen dead wood.

Steps

1. Establish 10 by 10 meter sub plots in two opposite corners- if the forest is homogeneous, sample from one corner can be adequate.
2. Identify the category
3. Measure diameter at three points of the fallen wood using measuring tape. The reading gives the diameter of the dead wood
4. Measure the height of the part of the down wood falling inside the sub-sample plot
5. Produce a disk from the fallen wood, weight the mass, take it to lab and measure the volume using the **flotation method**
6. Then calculate the density of the disk

$$\textbf{Density of the disk} = \frac{Mass\ of\ the\ disk}{Volume\ of\ the\ disk}$$

7. Using the volume formula, calculate the volume of the fallen dead wood
8. Then find the dry mass of the fallen wood from the density of the disk and volume of the fallen wood

$$\textbf{Dry mass of the dead wood} = \textbf{densityof the disk} * \textbf{volume of the fallen wood}$$

NB: Half of the dry mass is the carbon stock

5.3 Estimation of Litter

The litter pool includes dead organic surface materials less than 10 cm diameter. It is often considered an insignificant source in REDD projects, and inclusion of the litter pool as part of the project boundary is optional, as per applicability criteria in the framework module REDD-MF. The litter sample will be collected inside the same frames as the above ground non-woody vegetation.

Steps

1. Place the 1 by 1m frame at one of the four corners of the sample plot
2. Collect all litter inside the 1 by 1m frame and record the fresh weight
3. Take adequate sub-sample from the weighted sample and record the wet mass of the sub sample. Repeat the same in the remaining corners and at the center (5 times)
4. Label[3] the sub-samples and take them to laboratory, oven dry them and measure the dried mass
5. Estimate the dry mass of the original sample from the wet to dry ratio of the sub-sample as below

$$\textbf{Dry mass of the sample} = \frac{Sub\ sample\ dry\ mass}{Sub\ sample\ fresh\ mass} * Fresh\ Mass\ of\ the\ sample$$

6. Estimate the mean dry mass for the sample plot

[3] **Labeling litter**

$$\textbf{Mean litter dry mass per plot} = \frac{DM\ litter\ 1 + DM2 + DM3 + DM4 + DM5}{5\ (Or\ \#\ of\ subsamples)} * 10000m2$$

7. Estimate the mean biomass of the sample plot
8. Estimate the carbon stock in carbon dioxide equivalent

i.e. Litter carbon Stock= Mean biomass* 44/12

5.4. Estimating Below Ground Biomass

Measuring below ground tree biomass (roots) is difficult, time consuming, destructive and almost never measured, but instead is included through a relationship to above ground biomass (usually a root-to-shoot ratio). For tropical rainforest or humid forest, below ground biomass is estimated to be about 20% of the above ground biomass (woody and non -woody) estimates.

5.5 Estimation of Soil Carbon

Soil organic carbon shall be included if determined to be significant. Like litter and non-woody aboveground, soil samples will be taken from the four corners and at the center of the 1m by 1m sample frame

a) Soil Chemical Analysis

Steps

1. Take soil samples at the four corners and at the center of the big plot
2. Remove all organic layers (litter layer) and take samples of the 0-10, 10-20 and 20-30 cm soil depth. OR
3. Take soil sample using a soil auger (the length of the soil auger is 15 cm)

4. Mix the soil sample from three layers and take sub-sample (Composite) appropriately. It is also possible to thoroughly mix the composite samples from the five subplots and take one sample for chemical analysis
5. Label[4] the sub-sample and take it to laboratory
6. In the lab, air dry the subsample soil by placing it in a shallow try in a well ventilated, dust and wind free area
7. Sieve the soil sample through a 2 mm sieve and grind them in a mortar in order to pass through a 60 mesh screen
8. Conduct soil chemical (carbon) analysis using the right method

b) Soil Bulk Density Analysis

Steps

1. Avoid any place with possible soil compaction due to other sampling activities.
2. Remove the coarse litter layer and dig 30 cm deep and about 40 cm wide hole **(please note that it is possible to take composite soil sample for chemical analysis from the same peat)**
3. Take samples from 0-10, 10-20 and 20-30 cm depth using a core sampler of equal size
4. Transfer all soil from the core sampler into a plastic bag
5. Level[5] the samples separately

6. Take sub sample from each layer to lab
7. Oven dry the soil sample at 105 ^{0} C to constant mass
8. Measure the dry weight
9. Calculate the soil organic carbon

   i.e. Soil organic carbon stock= depth x carbon

6. Data Entry and Analysis

Data entry and computation of biomass is one of the key steps to generate carbon stock in carbon dioxide equivalent (ton per hectare) for REDD project developers. The selection of allometric equation should be given due emphasis in order to avoid under or over estimation of carbon stock. It is important to check the veracity of tree biomasses obtained from the allometric equation before proceeding to the next steps. DBH is the most common variable used for biomass calculation is DBH

6.1 Allometric Equations to Estimate Biomass

Traditionally, the determination of aboveground tree biomass has been conducted to ensure sustainable management of forest resources. Fuel wood management has motivated the calculation of biomass equations, whereas timber management has mainly driven volume equations. Today, the accurate estimation of forest biomass is crucial for many applications, from the commercial use of wood (Morgan and Moss 1985) to the global carbon (C) cycle (Bombelli et al. 2009). Because of interest in the global C cycle, estimating aboveground biomass with sufficient accuracy to establish the increments or decrements of C stored in forests is increasingly important.

Except in the very rare cases where a whole tree population can be harvested to determine its biomass (Augusto et al. 2009), the tree biomass is generally determined based on forest inventory data and allometric equations. The allometric method uses allometric equations to estimate the whole or partial (by compartments) mass of a tree from measurable tree dimensions, including trunk diameter and height (Kangas and Maltamo 2006). Thus, the dendrometric parameters of all of the trees are measured and the allometric equation is then used to estimate the stand biomass by summing the biomass of individual trees.

When building allometric equations for an individual tree, sprout or stand, different methods (destructive or not) may be considered. Destructive methods directly measure the biomass by harvesting the tree and measuring the actual mass of each of its compartments, (e.g., roots, stem, branches and foliage) (Kangas and Maltamo 2006). Indirect methods are attempts to estimate tree biomass by measuring variables that are more accessible and less time-consuming to assess (e.g., wood volume and gravity) (Peltier et al. 2007). Weighing trees in the field is undoubtedly the most accurate method of estimating aboveground tree biomass, but it is time-consuming and is generally based on small sample sizes. But more importantly, it is impractical to destructively sample the very trees for which reason a project is being implemented.

Species-specific allometric equations are preferred because tree species may differ greatly in tree architecture and wood gravity (Ketterings et al. 2001). However, in a tropical forest stand, more than 300 tree species may be found (Gibbs et al. 2007) and allometric equations should represent the variability of biomass for those species. As highlighted by McWilliam et al. (1993), destructive harvesting to build allometric models is seldom conducted in the tropics and sample plot sizes have been small compared to the scale of species diversity patterns; therefore, results may not be representative. Grouping all species together and using generalized allometric relationships that are stratified by broad forest types or ecological zones has been highly effective in the tropics (Brown 2002

While the use of generalized equations from Brown (1997), Chave et al. (2005) and Henry et al. (2010) for tropical rainforests are limited to trees with diameter (D1.3) <148, 156 and 180 cm, respectively, the estimation for trees with larger D1.3 is limited. The presence of trees with larger D1.3 is rare but does occur. For instance, Chave et al. (2003) reported that trees with D1.3 > 150 cm represent 9.75% of total biomass in a Brazilian tropical rainforest. Various authors have reported that increasing the number of predictors (and particularly incorporating the crown diameter and tree height) improves precision of the models.

Chave et al. (2005) reported that for tropical forests, the most important predictors of tree biomass were, in decreasing order of importance, trunk diameter at 1.3 m, wood specific gravity, total height and forest type. Gibbs et al. (2007) reported that D1.3 alone explains more than 95% of the variation in aboveground tropical forest carbon stocks. While the model developed by Brown (2002) explains 95% of the variability found in less than 150 tree samples.

Aalde et al. (2003) underlined that allometric models should not be used out of their domain of validity. Results show that generic biomass allometric models that include WSG as an explicative variable are preferable to models that do not, especially in dry forest ecosystems where species mean wood specific gravity is highly variable and can be very high.

Although several authors found WSG to be a key explicative variable for estimating tree biomass (Baker et al., 2004; Chave et al., 2005, 2009), models which do not include WSG are those suggested by many researchers. This represents a significant caveat to developing sound carbon estimates for REDD. The models which do not incorporate WSG were published in 1989 and 1997 and aimed at providing generic allometric models at a time when information on wood density was scarce. Today, reliable world data sets on wood densities exist (Chave et al., 2009; IPCC, 2006; Reyes et al., 1992; WAC, 2010) and methods have been proposed to estimate species wood density from phylogeny for use when information is not available at the species level (Baker et al., 2004; Slik, 2006).

In the evergreen forests of Ghana, Henry et al. (2010) also found that the Chave. H model provided accurate estimates of tree biomass (R2= 97% and mean bias = 3.74%). Considering that constructing allometric models specific to each country is destructive, time-consuming and expensive, we suggest using the Chave. H model as a first approximation to estimate tree biomass when country-specific allometric models are not available. The Chave.H model should be especially valuable in Africa, considering that the continent’s tropical forests represent 30% of the global total (FAO, 2005) and that almost no allometric models are available for Africa (but see Henry et al. (2010) and Kaonga and Bayliss-Smith (2010)).

7. General guidance to reduce error in biomass estimation

At every stage of research there are sources of error and uncertainty. Hence, attempting to identify and quantify these is crucial in order to realistically take measures to reduce its effects on the final outcome of the inventory. Below is a summary of some common errors that should be noted in conducting field work and also during the data analysis.

7.1. Error associated with the Use of local names to identify tree species

1. Local names are sometimes spelled slightly differently in different localities, but are considered the same
2. Local names that are very similar can refer to totally different species,
3. Some species don't seem to have scientific name(see annex 4),
4. Some local names refer to more than one species,
5. Some species have more than one local name,

7.2. The use of wood specific gravity (WSG)

It is a good practice to determine the WSG of each species from established databases and sources. However, on occasions where the WSG of a particular species cannot be found, the best approach is to calculate the average value of the genus or family and assign it to the unknown species. Where WSG could not be found at family level, or the tree identity was indeterminate, the average WSG of all samples can be used.

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Annex 1:

Field Data Collection Formats

Table A1: Above Ground Biomass Field Inventory From

Plot Number:	**Land use type:**
Latitude:	**Age of land use type:**
Longitude:	**Recorder:**
Nest:	**Date:**
GPS and compass reading of the Nest	

Plant ID[1]	**Species**2	**Category**[3]	**D 1 (cm)**4	**D 2 (cm5**	**H (m6**	**Remark**[7]

Annex 2

Data entry format

Species		Nest	Plot area	Parameters				C stock		
Local name	Scientific name			Wood Density (g/cm^3)	DBH (cm)	Height (m)	Biomass (kg)	C Stock (kg)	C Stock (ton/ha)	C stock in CO_2 equivalent

Annex 3

General Allometric Equations

Ecological zone	Reference	Equation	Variables
Tropical rainforest	Brown, S.(1997)	Y (kg) =21.297-6.953*(X)+0.740*((X^2))	X= DBH(cm)
Tropical moist deciduous forest	Brown, S.(1997)	Y (kg) =42.69-12.800*(X)+1.242*((X^2))	X= DBH(cm)
Tropical dry forest	Brown, S.(1997)	Y (kg) =exp(-1.996+2.32*ln(X))	X= DBH(cm)
Tropical dry forest	Brown, S.(1997)	Y (kg) =10^(-0.535+ln(X))	X= DBH(cm)
Tropical dry forest	Brown, S.A.J. et al.. (1989)	Y (kg) =34.4703-8.0671*X+0.6589*(X^2)	X= DBH(cm)
Tropical shrubland	Brown, S.A.J. et al.. (1989)	Y (kg) =34.4703-8.0671*X+0.6589*(X^2)	X= DBH(cm)
Tropical rainforest	Brown, S.A.J. et al.. (1989)	Y (kg) =exp(-3.1141+(0.9719*ln(((X^2)*Z)))	X= DBH(cm),Z= H(m)
Tropical moist deciduous forest	Brown, S.A.J. et al.. (1989)	Y (kg) =exp(-3.1141+(0.9719*ln((X^2)*Z)))	X= DBH(cm),Z= H(m)
Tropical rainforest	Brown, S.A.J. et al.. (1989)	Y (kg) =exp(-2.4090+(0.9522*ln((W^(2))*X*Z)))	X= DBH(cm),Z= H(m), Z= As(m2)
Tropical moist deciduous forest	Brown, S.A.J. et al.. (1989)	Y (kg) =exp(-2.4090+(0.9522*ln((W^(2))*X*Z)))	X= DBH(cm),Z= H(m), Z= As(m2)
Tropical rainforest	Ponce-Hernandez, R.(2004)	Y (kg) =exp(2.134+(2.530*ln(X)))	X= DBH(cm)
Tropical moist deciduous forest	Ponce-Hernandez, R.(2004)	Y (kg) =exp(2.134+(2.530*ln(X)))	X= DBH(cm)
Tropical dry forest	Chave, J. et al. (2005)	Y (kg) =X*exp(-0.667+(1.784*ln(Z))+(0.207*(ln(Z))^2)-(0.0281*(ln(Z))^3))	X= WD(g.cm-3),Z= DBH(cm)
Tropical dry forest	Chave, J. et al. (2005)	Y (kg) =exp(-2.187+(0.916*ln(X*Z^2*W)))	X= WD(g.cm-3),Z= DBH(cm), Z= H(m)
Tropical moist deciduous forest	Chave, J. et al. (2005)	Y (kg) =X*exp(-1.499+(2.148*ln(Z))+(0.207*(ln(Z))^2)-(0.0281*(ln(Z))^3))	X= WD(g.cm-3),Z= DBH(cm)
Tropical moist deciduous forest	Chave, J. et al. (2005)	Y (kg) =exp(-2.977+ln(X*Z^2*W))	X= WD(g.cm-3),Z= DBH(cm), Z= H(m)

Tropical rainforest	Chave, J. et al. (2005)	Y (kg) =exp(-2.977+ln(X*Z^2*W))	X= WD(g.cm-3),Z= DBH(cm), Z= H(m)
Tropical rainforest	Chave, J. et al. (2005)	Y (kg) =X*exp(-1.349+(1.980*ln(Z))+(0.207*(ln(Z))^2)-(0.0281*(ln(Z))^3))	X= WD(g.cm-3),Z= DBH(cm)
Tropical rainforest	Chave, J. et al. (2005)	Y (kg) =exp(-2.557+0.940*ln(X*Z^2*W))	X= WD(g.cm-3),Z= DBH(cm), Z= H(m)
Tropical rainforest	Chave, J. et al. (2005)	Y (kg) =X*exp(-1.239+(1.98*ln(X))+(0.207*(ln(X))^2)-(0.0281*(ln(X))^3))	X= WD(g.cm-3),Z= DBH(cm)
height-diameter relationship	Lewis, S.L. et al. (2009)	H (m) = 54.01 * (1-exp(-0.053(d^0.759)))	d = DBH (mm)
	Henry, M et al., 2010	Y=3.47*10^-3*d^(2)*h*wd	d=DBH, h=height, wd= wood density

Annex 4

Species Specific Allometric Equations

General Classification	Species Group	Equation	Source	Data originating from	Max DBH
Shade grown	*Coffea Arabica*	Biomass=exp(-2.719 + 1.991 (ln(dbh))) (log10dbh)	Segura et al. 2006	Nicaragua	8 cm
Pruned coffee	*Coffea Arabica*	Biomass = 0.281 x $dbh^{2.06}$	Van Noordwijk et al. (2002)	Java, Indonesia	10 cm
Banana	*Musa X paradisiacal*	Biomass = 0.030 x $dbh^{2.13}$	Van Noordwijk et al. (2002)	Java, Indonesia	28 cm
Orange trees	*Citrus sinensis*	Biomass = -6.64 + 0.279 x BA + 0.000514 x BA^2	Schroth et al. (2002)	Amazonia	8–17cm
Lianas	Lianas	Biomass = exp(0.12+0.91xlog (BA at dbh))	Putz (1983)	Venezuela	12 cm