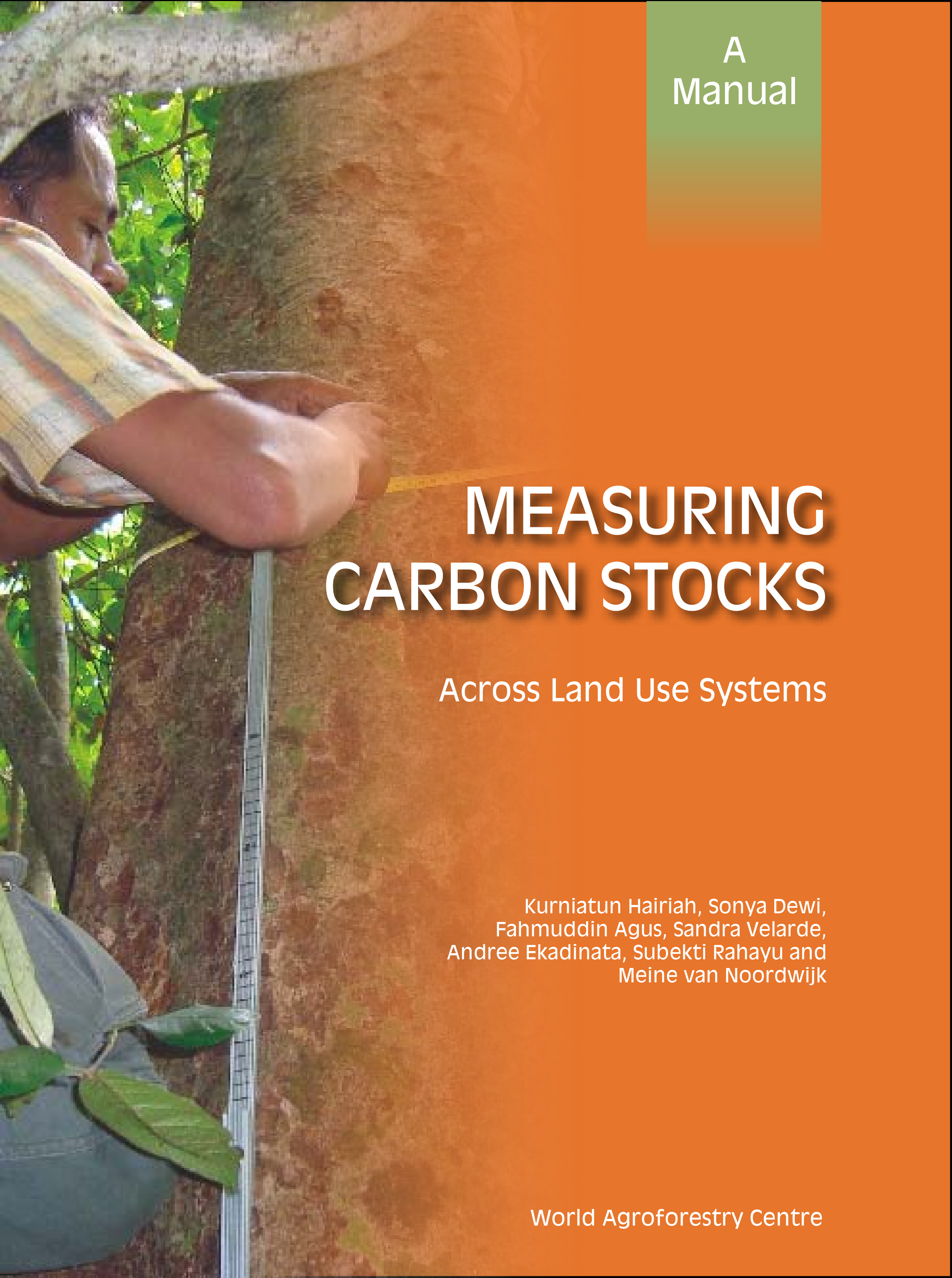

A
Manual

MEASURING CARBON STOCKS

Across Land Use Systems

Kurniatun Hairiah, Sonya Dewi,
Fahmuddin Agus, Sandra Velarde,
Andree Ekadinata, Subekti Rahayu and
Meine van Noordwijk

World Agroforestry Centre

A manual

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Kurniatun Hairiah dan Daud Pateda

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Hairiah K, Sitompul SM, van Noordwijk M and Palm, CA, 2001 Methods for sampling carbon stocks above and below ground. ASB_LN 4B.

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Preface

Without ‘greenhouse gases’, planet Earth would not support life as we know it; however, the actual amount of heat trapped in the atmosphere is in a delicate balance with the climatic systems and ocean currents of the globe. Rapid increases in atmospheric CO_2 concentrations that we have witnessed over the last century, along with increases in other ‘greenhouse gases’, are a risk to humans. Beyond the gradual changes in climate already noted, larger-scale changes in global circulation systems can follow that may be dramatic in their consequences. In response, the global community has agreed to control the net release of greenhouse gases from both fossil fuel sources and from changes in terrestrial C stocks. Details on how to do this are still being negotiated, but reliable data are needed to move from general commitments to specific actions and to monitor their effectiveness. This Manual of methods aims to contribute to such a process, focusing on changes in terrestrial carbon stocks linked to land use.

In the exchange of carbon dioxide (CO_2) between terrestrial vegetation and the atmosphere, the net balance between sequestration and release shifts from net accumulation to net carbon (C) release on a minute-by-minute timescale, for example, with cloud interception of sunlight, in a day-night pattern, across a seasonal cycle of dominance of growth and decomposition, and with the stages of the lifecycle of a vegetation or land use system. We focus here on the latter timescale, as part of the annual (or 5-yearly) accounting of land use and land use change. At this timescale, many fluxes can be expected to cancel each other out and we can focus on the net changes in the carbon stock, as the ‘bottom-line’ of many influx (gain) and efflux (loss) processes.

The annual net effect of photosynthesis and respiration (decomposition) is a relatively small increment in stored carbon in most years, often balanced by drought years where fire consumes organic matter and the accumulated gains are lost. Only small amounts of stored carbon may leach out of soils and enter long-term storage pools in freshwater or ocean environments, contribute to peat formation or the source of methane burping in wetlands. Part of the organic products (such as wood, resin, grain and tubers) leave the area of production and are incorporated into trade flows, usually ending up concentrated in urban systems and their waste dumps. Tropical forests in their natural condition contain more aboveground C per unit area than any other land cover type. Where forests that have stored C during a century or more of small annual increments in tree biomass are converted to more open vegetation, a large net release to the atmosphere occurs, either in a matter of hours in the case of fire, during a number of years due to decomposition, or over periods of up to decades where wood products enter domestic/urban systems. The net emissions can be estimated from the decrease or increase in the terrestrial C stocks, for example, when an annual accounting step is used.

Consistent accounting for all the inflows and outflows is more complex than a simple check of the bottom line change in total stock. Current estimates suggest that land use, land use change and forestry (LULUCF) is responsible for 10–20% of total greenhouse gas emissions (Houghton, 2005; van der Werf *et al*., 2009; Dolman *et al*. 2010); the lower estimates use higher total emission data from all sources). Net sequestration in temperate zones and large net emissions in the tropics are based on this type of stock accounting, with high emission estimates relative to the small source areas contributed by tropical peat areas (IPCC, 2006).

Virtually all types of C accounting rely on remote sensing for spatial extrapolation and analysis of temporal change of ground-based carbon stock measurement. As existing data tend to be of varying type and quality, a synthesis of such data may well identify gaps and areas of weakness, where fresh data collection is warranted. The uncertainty in total estimates depends on the scale at which they are made—national-scale estimates can be less uncertain than the sum of sub-national entities—but the way the various types of uncertainty interact depends on their degree of bias versus random measurement error. Recently, re-analysis of wood density data for the forest types in Brazil that have the highest loss rate led to a claim that existing national estimates were 10% too high (Nogueira *et al*., 2007). If research can still lead to a 10% reduction in accountable emissions, the challenge to deal with real emissions through policy commitments and economic instruments is increased: the tolerance for uncertainty in emission data is low if substantial amounts of money (and prestige) are involved.

The current version of this Manual represents the next step in a process that started in the early 1990s when the Alternative to Slash and Burn (ASB) program started efforts to collect consistent data across the humid tropics (Palm *et al*., 2005). With growing interest in the topic, other manuals and guidelines have been developed by various organizations, but most focus on 'forest' and few deal with the full range of land use types that are found in most forest-derived landscapes.

The Manual is consistent with the Good Practice Guideline (GPG) of the Intergovernmental Panel on Climate Change (IPCC) that is to be used for national accounting of carbon stocks and greenhouse gas emissions. The GPG discusses the information, in terms of classification, area data, and sampling that are needed to estimate the carbon stocks and the emissions and removals of greenhouse gases associated with Agriculture, Forestry and Other Land Use (AFOLU) activities. These guidelines require that all data be:

- ***Adequate***, 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***, that is, capable of representing land use categories consistently over time, without being unduly affected by artificial discontinuities in time-series data;
- ***Complete***, which means that all land within a country should be included, with increases in some areas balanced by decreases in others, recognizing the bio-physical stratification of land if needed (and as can be supported by data) for estimating and reporting emissions and removals of greenhouse gases; and
- ***Transparent***, that is, data sources, definitions, methodologies and assumptions should be clearly described.

The Manual aims to provide a background that allows methods to be transparent and then provide a 'how to do it' guide that is adequate, consistent and complete.

The authors

1

photo: Kurniatun Hairiah

Trees in the landscape draw carbon dioxide from the atmosphere and store part of that in their wood for the rest of their life-time and a little beyond

PART 1: Background: Why do you want to measure carbon stocks across land use systems?

1.1 The global carbon cycle

1.1.1 The big picture

During geological history, the emergence of plants on earth has led to the conversion of carbon dioxide (CO_2) in the atmosphere and oceans into innumerable inorganic and organic compounds on land and in water. The 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

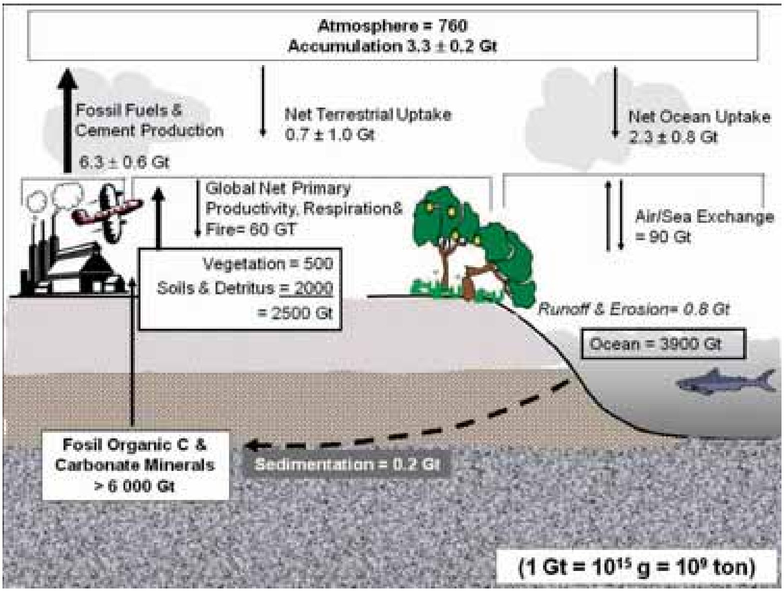

Figure 1. The global C-cycle showing the C stocks in reservoirs (in Gt = 10^{15}g = 10^9 tonne) and C flows (in Gt yr^{-1}) relevant to anthropogenic disturbance, as annual averages over the decade from 1989 to 1998 (based on Schimel *et al.*, 1996, cited in Ciais *et al.*, 2000).

history, with more CO_2 in its atmosphere and a stronger greenhouse gas effect trapping solar energy (Appendix 1). Background to the climate change debate and its relation to greenhouse gases and CO_2 are provided in Appendix 1, but also can be found in many popular texts and on websites. Figure 1 shows the global C cycle between C stocks and flows in reservoirs and in the atmosphere. 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 tonne (Gt) = 10^9 t = 10^{15} g = 1 Pg). The next largest stock, fossil C, accounts for only 6,000 Gt. Furthermore, the terrestrial C stocks (see Box I) 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.

Box 1. What are carbon stocks?

‘Terrestrial carbon stocks’ is the term used for the C stored in terrestrial ecosystems, as living or dead plant biomass (aboveground and belowground) and in the soil, along with usually negligible quantities as animal biomass (see part 2.4). Aboveground plant biomass comprises all woody stems, branches and leaves of living trees, creepers, climbers and epiphytes as well as understory plants and herbaceous growth. For agricultural lands, this includes trees (if any), crops and weed biomass. The dead organic matter pool (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. The belowground biomass comprises living and dead roots, soil fauna and the microbial community. There also is a large pool of organic C in various forms of humus and other soil organic C pools. Other forms of soil C are charcoal from fires and consolidated C in the form of iron-humus pans and concretions. For peatland, the largest C pool is found in soil (See part 2). Peat soils can store 10–100 times more carbon per unit area than other areas and are thus of special interest for the global C cycle.

1.1.2 Timescales

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 (Figure 2). 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. The focus in this Manual is on the latter timescale, as part of the annual (or 5-yearly) accounting of land use and land use change. At this timescale, many fluxes can be expected to cancel out and allow focus on the net changes in the 'bottom line'.

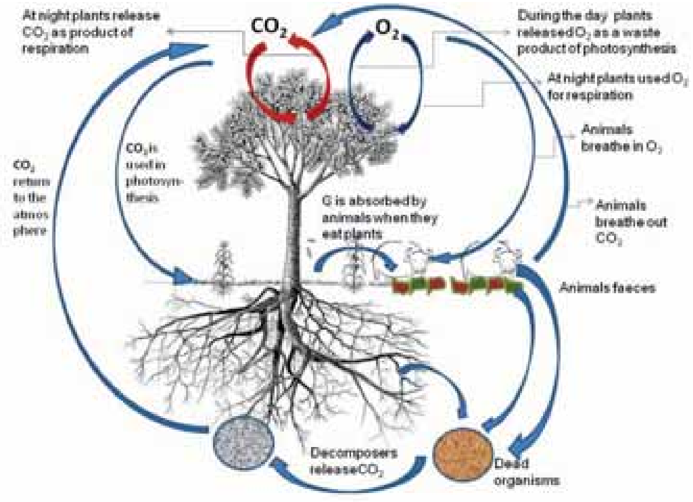

Figure 2. Illustration of carbon cycle at plot level (quoted from http://www.energex.com.au/switched_on/being_green/being_green_carbon.html).

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 (see Box 2). At nighttime and at times that plants don't have active green leaves, the reverse process of 'respiration' dominates, in which organic compounds are decomposed, absorbing O_2 in the process of respiration.

a. Annual 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.

Box 2. What is photosynthesis?

Photosynthesis is the process by which green plants use carbon dioxide (CO_2), water (H_2O) and sunlight to make their own food. The word photosynthesis means “to put together with light”. When all these components are put together they make sugar and oxygen (O_2).

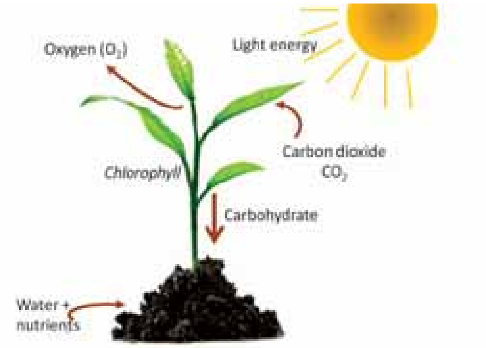

Figure 3. Photosynthesis diagram (available from: http://bioweb.uwlax.edu/bio203/s2008/brooks)

Continued...

Plants take in carbon as CO_2 through the process of photosynthesis and convert it into sugars, starches and other materials necessary for the plant's survival. From the plants, carbon is passed up the food chain to all the other organisms. This occurs when animals eat plants and when animals eat other animals.

Photosynthesis removes CO_2 from the air and adds oxygen, while cellular respiration removes oxygen from the air and adds CO_2. The processes generally balance each other out.

Both animals and plants release CO_2 as a waste product. This is due to a process called cell respiration, where the cells of an organism break down sugars to produce energy for the functions they are required to perform. The equation for cell respiration is:

Glucose + Oxygen → Energy + Water + Carbon Dioxide

for example, $C_6H_{12}O_6 + {}_6 0_2 \rightarrow \text{Energy} + {}_6H_2O + {}_6CO_2$

CO_2 is returned to the atmosphere when plants and animals die and decompose. The decomposition releases CO_2 back into the atmosphere where it will be absorbed again by other plants during photosynthesis. In this way, the cycle of CO_2 being absorbed from the atmosphere and being released again forms a never-ending cycle.

In the carbon cycle, the amount of carbon in the environment always remains the same. However, in the last 200 years, the burning of fossil fuels and deforestation has increased the amount of atmospheric carbon dioxide from 0.028 to 0.035% and the concentration is continuing to increase. The increase in CO_2 is accompanied by an equivalent decrease in the O_2 concentration, but because the O_2 concentration is so much higher (above 20% of the atmosphere), this decline is hardly noticeable and not of any real concern.

b. Decadal patterns of buildup of 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.

c. Century-scale build up of peat soils

Carbon captured in photosynthesis can move from the vegetation into the soil. This happens first of all during the growth of roots, which form the basis of a belowground food web through fungi, bacteria and all the animals that feed on them. Part of the soil fauna is also able to incorporate dead leaves into the soil and the soil becomes tightly linked with the litter layer on top that is formed by dead leaves and other parts of plants such as twigs, flowers or fruits. While in the end, much of the plant-derived organic matter is respired in this food web, part of the organic material develops a chemical form that resists decomposition or becomes tightly bound to clay or silt particles and thus is protected from decomposition. Under conditions that are still not fully understood, the decomposition is so much slower than the rate of fresh organic inputs that peat layers start to build up, even under warm and humid conditions, but assisted by high water tables and a low supply of oxygen. As peat soils have a low pH and low nutrient content, the subsequent organic inputs will decompose more slowly and the process of peat formation can be reinforced. The buildup of peat soils can take centuries or thousands of years, and despite the low rates of plant growth, peat vegetation is one of the most effective long term C storage mechanisms.

*) The Global Carbon Budget is zero. Its components, however, are of interest, as they balance the exchanges (incomes and losses) of carbon between the carbon reservoirs or between one specific loop (for example, atmosphere↔biosphere) of the carbon cycle. An examination of the carbon budget of a pool or reservoir can provide information about whether the pool or reservoir is functioning as a source or sink for carbon dioxide.

1.1.3 Carbon sequestration at multiple scales

The representation of multiple time scales (elaborated in section 1.2.2, the analysis of carbon budgets) can be done at multiple temporal scales, but the results need to be interpreted differently. The different scales are indicated by acronyms such as GPP, NPP, NEP and NBP (see Figure 4B quoted from IPCC, 2000), as follows:

- ***Gross Primary Production (GPP)*** denotes the total amount of C fixed in the process of photosynthesis by plants in an ecosystem, such as a stand of trees. GPP is measured on photosynthetic tissues, principally leaves, on an hourly timescale and integrated to an annual amount. Global total GPP is about 120 Gt C yr^{-1}.
- ***Net Primary Production (NPP)*** denotes the net production of organic matter by plants in an ecosystem. NPP is about half of GPP as plants respire the other half in building up and maintaining plant tissues. NPP can be measured as the increase in plant biomass on a daily or weekly timescale. For all terrestrial ecosystems combined, it is estimated to be about 60 Gt C yr^{-1}.
- ***Net Ecosystem Production (NEP)*** denotes the net accumulation of organic matter or C by an ecosystem; NEP is the difference between the rate of production of living organic matter and the decomposition rate of dead organic matter (heterotrophic respiration). Heterotrophic respiration includes losses by herbivore and the decomposition of organic matter by organisms. Global NEP is estimated to be about 10 Gt C yr^{-1}. NEP can be measured in two ways: one is to measure changes in C stocks in vegetation and soil over time, using an annual timescale; the other is to integrate hourly/daily fluxes of CO_2 into and out of vegetation and integrate up to the yearly timescale. NEP should be integrated up to a decadal (10 year) timescale.
- ***Net Biome Production (NBP)*** denotes the net production of organic matter in a region containing a range of ecosystems (a biome) and includes, in addition to heterotrophic respiration, other processes leading to loss of living and dead organic matter (harvest, forest clearance and fire, among others). Compared to the total fluxes between the atmosphere and biosphere, global NBP is comparatively small at 0.7–1.0 Gt C yr^{-1}. It can be measured only at a decadal or longer time frame, as the disturbances

> that are to be taken into account do not occur every year. The distinction between disturbances which are natural and those which are at least partly caused by humans is complex, especially where fire is involved.

The timescale selected for measurements is critical for the interpretation of results. The scale of ***Net Ecosystem Productivity*** is most appropriate in discussing the impacts of land cover/land use change on global emissions for two reasons. First, even though net biome productivity (NBP) is most relevant in terms of timescale for global change debates, in order to calculate NBP it is necessary to measure the net ecosystem productivity (NEP) and account separately for the disturbances (including harvests) which usually happen over a shorter timescale than a decade. This also relates to the time frame of climate change mitigation actions and strategies under international agreements; a decade is simply too long and hardly relevant. Secondly, it is feasible to calculate NEP for a large area and technically optimal regarding the uncertainty level. If C fluxes are measured on an hourly basis as gross primary productivity (GPP) and plant respiration, then it is necessary to deal with very large numbers in either direction. This measurement is not feasible if a large area of interest is to be covered, not to mention global analysis. In addition, the uncertainties in the measurements will make it difficult to assess the small differences between losses and gains.

Net ecosystem productivity (NEP) can be assessed as **a time-averaged C stock** of the system (Hairiah *et al*., 2001; IPCC-LULUCF (section 4), 2000), or 'typical C stock' (White *et al*., 2010. Time-averaged C stocks of a land use system records the amount of C stocks that are actually present *in situ*, averaged over the life cycle of such a land use system. The key then is to be able to quantify the current (on-site) C stock at any stage of the life cycle of a land use system and scale up to the typical life cycle. At this timescale, many fluxes can be expected to cancel out and we can focus on net changes to the bottom line. Time-averaged C stock is discussed in Part II.

1.1.4 Special roles of forest?

The vegetation of tropical forest is a large and globally significant storage of C because tropical forest contains more C per unit area than any other land cover. 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. About 50% of plant biomass consists of C. The carbon stored in the aboveground living biomass of trees is typically the largest pool and the most directly impacted by deforestation and degradation.

The C stock in an individual tree depends on the tree's size. For trees of 10, 30, 50 or 70 cm stem diameter (measured at a standard 1.3 m above the ground and known as the diameter at breast height or DBH), the biomass may be around 135, 2250, 8500 or 20,000 kg/tree, respectively. A forest with stocking of 900, 70, 20 and 10 such trees per ha, will have a total biomass of 645 Mg ha^{-1}, with a corresponding C stock of 290 Mg ha^{-1}, with 19, 24, 26 and 31% in the respective diameter classes. Most of the biomass is in the few really big trees.

Cutting down trees in the forest releases C to the atmosphere. Although selective logging may only remove a few big trees per area (and damage surrounding ones), it can lead to a substantial decrease in total biomass and C stock.

Large trees tend to have large roots. For mixed tropical forest, the ratio of aboveground to belowground biomass is approximately 4:1; in very wet conditions, the ratio can shift upwards to 10:1, while under dry conditions it may decrease to 1:1 (van Noordwijk *et al*., 1996, Houghton *et al*., 2001, Achard *et al*., 2002, Ramankutty *et al*., 2007 *et al*.). As measurement of root biomass is not simple (Smit *et al*., 2000) there is a method that uses the root diameter at stem base and allometric equations (van Noordwijk and Mulia, 2002), default assumptions are normally used for the shoot:root ratio based on literature reviews (van Noordwijk *et al*., 1996; Cairns *et al*., 1997; Mokany *et al*., 2006).

When forests (with an average of 250 Mg C ha^{-1}) are transformed to agricultural activities, the subsequent land use systems implemented determine the amount of potential carbon restocking that takes place. On average, annual crop systems will contain only 3 Mg C ha^{-1} and intensive tree crop plantations 30–60 Mg C ha^{-1} (Tomich *et al*., 1998; Palm *et al*., 2005), or 1 and 10–25% of the forest biomass and C stock, respectively. The annual

C sequestration rate (increment of standing stock) may be the same (about 3 Mg C ha^{-1} yr^{-1}) for all three vegetation types (annual crop, tree plantation and forest), but the mean residence time differs from 1, 10 to 83 years, respectively. Changes in C stock between vegetation and land use types relate primarily to this mean residence time.

Thus, estimating aboveground forest biomass carbon is the critical step in quantifying carbon stocks and fluxes from tropical forests. Root biomass is estimated to be 20% of the aboveground forest carbon stocks for most forest types, but it can be less than 10% or more than 90% in specific vegetation types (for example, Houghton *et al*., 2001, Achard *et al*., 2002, Ramankutty *et al*., 2007; van Noordwijk *et al*., 1996) based on a predictive relationship established from extensive literature reviews (Cairns *et al*., 1997, Mokany *et al*., 2006). Reliable estimates of biomass, litter and soil carbon are needed to understand the effect of forests on atmospheric carbon dioxide. Forest inventories that focus on harvestable timber often need to be augmented to quantify the whole carbon budget of the forest (Figure 4).

(A)

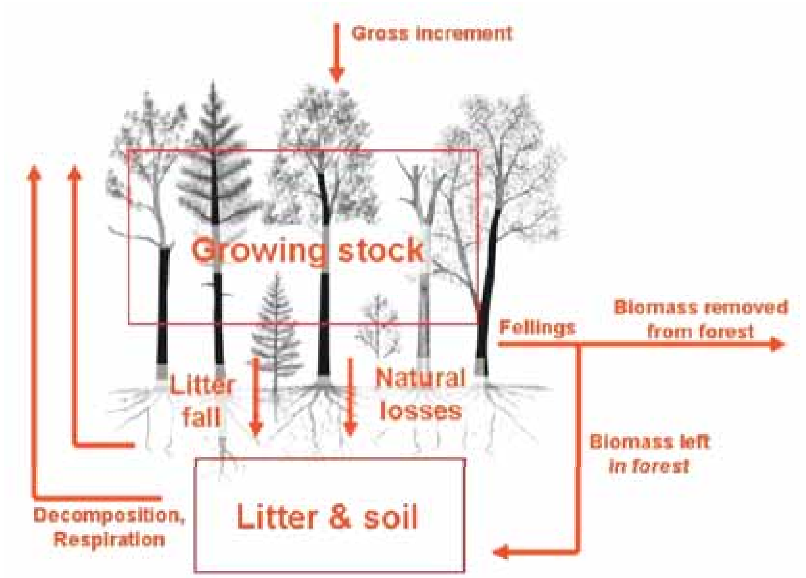

Figure 4. (A) Illustration of forest inventory-based approach to estimate carbon budgets, where estimates of stem volume of growing stock, gross increment and fellings are converted to biomass, which is further converted to litterfall with turnover rates and the estimated litterfall is fed into dynamic soil carbon. This approach gives directly estimates of changes in the carbon stock of trees and forest soil (available from: http://www.helsinki.fi/geography/research)

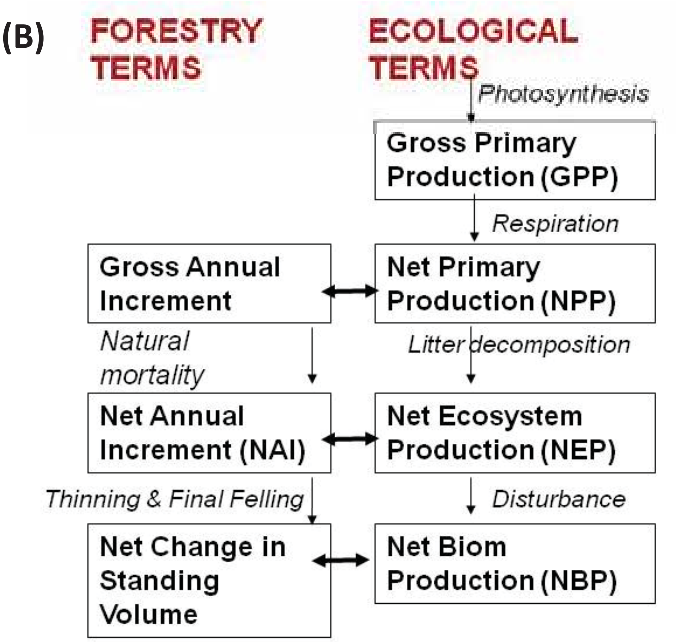

Figure 4. (B) Equivalent terms as used in Forestry and Ecological research.

For the same reason, trees growing either inside or outside the forest take up C from the atmosphere and store it as biomass for a long time. Natural forests can reach a biomass equilibrium stage when the collapse of a big tree matches the growth of the smaller trees surrounding it, but tree mortality tends to be concentrated in years of exceptional weather. Total biomass shifts up and down at a patch level but is approximately constant at the level of a forest or forested landscape in the absence of logging and other human disturbance. In practice, however, many forests are still recovering from previous levels of human exploitation as well as natural disturbance.

While old-growth forests have the highest aboveground C stock, they usually have a low rate of further C sequestration. Other forests (‘younger’ in ecological terms) may have less C stock (Box 3), but a higher rate of accumulation. Grasslands and pioneer vegetation may have the highest rate of C gross primary productivity, but low stocks and low inter-annual increment in storage. However, given this range, there is no reason to treat forests differently from other vegetation types in the assessment of terrestrial C stocks. There should be no confusion regarding the time frame over which comparisons are to be made.

Box 3. Case study: Measurement of C stocks of different land use types

Aboveground carbon storage in natural forest is higher than that in any other vegetation, but total C storage can be higher in peat ecosystems (with or without forest). Based on methods that will be explained in Part 2, an overview of C stocks in different land use systems in the humid tropics was obtained by ASB scientists in the early 1990's (Figure 5).

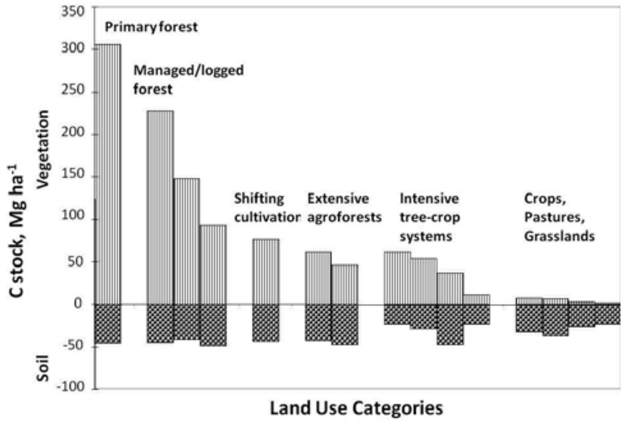

Figure 5. Aboveground time-averaged carbon stocks and total soil C (0–20 cm) for land uses in benchmark sites in Indonesia, Cameroon and Brazil. Details of data collection are explained in Part 2.

The magnitude of losses and potential C sequestration with transitions between the various land uses can be estimated from the summary data. For example, C losses from converting natural forests to logged forests range from a low of 80 Mg C ha^{-1} to a high of 200 Mg C ha^{-1}. The majority of the C is lost from the vegetation with little loss from the soil. If the logged forests are further converted to continuous cropping or pasture systems, an additional 90 to 200 Mg C ha^{-1} are lost aboveground and 25 Mg C ha^{-1} are lost from the topsoil. Losses from conversion of logged forests to other tree-based systems are smaller, from 40 to 180 Mg C ha^{-1} aboveground and 10 Mg C ha^{-1} from the soil. If croplands and pastures were rehabilitated through conversion to tree-based systems, then this would result in net carbon sequestration. Over a 25-year period, the amount of C that could be sequestered would range from 5 to 60 Mg C ha^{-1} aboveground and 5 to 15 Mg C ha^{-1} in the topsoil. The main point is that the potential for C sequestration in the humid tropics is aboveground, not in the soil.

1.2. International agreements

1.2.1 United Nations Framework Convention on Climate Change

A total of 192 countries in the world have joined an international treaty—the United Nations Framework Convention on Climate Change (UNFCCC)—to begin to consider what can be done to reduce global warming and to cope with whatever temperature increases are inevitable.

Box 4. Adaptation and mitigation to climate change

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCC) and any related legal instruments that the Conference of the Parties (COP) may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Most, but not all, nations have also approved an addition to the treaty: the Kyoto Protocol, which entered into force on 16 February 2005 and which has more powerful (and legally binding) measures, focused on the first commitment period of 2008–2012.

The Convention places the heaviest burden for fighting climate change on industrialized nations, since they are the source of most past and current greenhouse gas emissions. These countries are asked to do the most to cut what comes out of smokestacks and tailpipes, and to provide most of the money for efforts elsewhere. For the most part, these developed nations (called Annex I countries because they are listed in the first annex to the treaty) belong to the Organization for Economic Cooperation and Development (OECD). These advanced nations, as well as 12 “economies in transition" (countries in Central and Eastern Europe, including some states formerly belonging to the Soviet Union) were expected by the year 2000 to reduce emissions to 1990 levels. As a group, they succeeded. Industrialized nations agreed under the Convention to support climate-change activities in developing countries by providing financial support above and beyond any financial assistance they were already providing to these countries. Because economic development is vital for the world's poorer countries—and because such progress is difficult to achieve even without the complications added by climate change—the Convention accepts that the share of greenhouse gas emissions produced by developing nations will grow in the coming years. Nonetheless, it seeks to help such countries limit emissions in ways that will not hinder their economic progress. The Convention acknowledges the vulnerability of developing countries to climate change and calls for special efforts to ease the consequences. While developing countries have not so far agreed to commit themselves to any level of emissions (per capita or per country), they have an obligation to report their emissions and C stocks to assist in the global bookkeeping of emissions and the drivers of climate change. Developing countries that want to participate in other mechanisms of the Convention will need to provide such data, as part of global transparency.

1.2.2 IPCC reporting standards

Parties to the Convention must submit national reports on the implementation of the Convention to the Conference of the Parties (COP), in accordance with the principle of "common but differentiated responsibilities" enshrined in the Convention. The core elements of the national communications for both Annex I and non-Annex I Parties are information on emissions and removals of greenhouse gases (GHGs) and details of the activities a Party has undertaken to implement the Convention. National communications usually contain information on national circumstances, vulnerability assessment, financial resources, transfer of technology, education, training and public awareness, but the ones from Annex I Parties additionally contain information on policies and measures. Annex I Parties are required to submit information on their national inventories annually and to submit national communications periodically, according to dates set by the COP. There are no fixed dates for the submission of national communications by non-Annex I Parties, although these documents should be submitted within four years of the initial disbursement of financial resources to assist them in preparing their national communications.

Box 5. Formal obligations as part of the UNFCCC convention

Article 4, paragraph 1(a): Develop, periodically update, publish and make available to the Conference of the Parties, in accordance with Article 12, national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases (GHGs)* not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the Conference of the Parties.

(* including inventories of GHG emissions and removals from the LULUCF sector)

Article 4, paragraph 1(d): Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all GHGs not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems

Accurate, consistent and internationally comparable data on GHG emissions is essential for the international community to take the most appropriate action to mitigate climate change and ultimately to achieve the objective of the Convention. Communicating relevant information on the most effective ways to reduce emissions and adapt to the adverse effects of climate change also contributes towards global sustainable development.

The first global guidelines for reporting on the land use component were internationally agreed in 1996 as “LULUCF” (land use, land use change and forestry). This was followed in 2003 by the “Good Practice Guidance for Land Use, Land Use Change and Forestry” (GPG-LULUCF) as the response to the invitation by the United Nations Framework Convention on Climate Change (UNFCCC) to the Intergovernmental Panel on Climate Change (IPCC) to develop good practice guidance for land use, land use change and forestry (LULUCF).

A revised version that ironed out some inconsistencies was ratified in 2006 as “AFOLU” (agriculture, forestry and other land uses). The categories within the good practice guideline (GPG) for different land uses are presented in Box 5, in which non-ambiguous land categories are assumed. However, in practice, these often still present some confusion and inconsistency. For example, where does a rubber agroforest on peatland belong? It meets the minimum tree height and crown cover of forest, but is on a wetland and its production is recorded under agricultural statistics. Consistency of accounting methods across land categories requires a good understanding of such relations.

Box 6. Levels of sophistication (tiers) in GHG accounting

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html) provided a framework 3-tiered structure for AFOLU (Agriculture, Forestry and Other Land Use is the name for historical reasons; it might just as well be called 'all land use') methods:

> *"**Tier 1** methods are designed to be the simplest to use, for which equations and default parameter values (e.g., emission and stock change factors) are provided in this volume. Country-specific activity data are needed, but for Tier 1 there are often globally available sources of activity data estimates (e.g., deforestation rates, agricultural production statistics, global land cover maps, fertilizer use, livestock population data, etc.), although these data are usually spatially coarse."*

> *"**Tier 2** can use the same methodological approach as Tier 1 but applies mission and stock change factors that are based on country- or region-specific data, for the most important land use or livestock categories. Country-defined emission factors are more appropriate for the climatic regions, land use systems and livestock categories in that country. Higher temporal and spatial resolution and more disaggregated activity data are typically used in Tier 2 to correspond with country-defined coefficients for specific regions and specialized land use or livestock categories."*

Continued...

> *"At **Tier 3**, higher order methods are used, including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution activity data and disaggregated at sub-national level. These higher order methods provide estimates of greater certainty than lower tiers. Such systems may include comprehensive field sampling repeated at regular time intervals and/or GIS-based systems of age, class/production data, soils data, and land use and management activity data, integrating several types of monitoring. Pieces of land where a land use change occurs can usually be tracked over time, at least statistically. In most cases these systems have a climate dependency, and thus provide source estimates with inter-annual variability. Detailed disaggregation of livestock population according to animal type, age, body weight etc., can be used. Models should undergo quality checks, audits, and validations and be thoroughly documented."*

The current Manual is intended to provide data that can be summarized for Tier 2 approaches, or feed into more sophisticated Tier 3 methodology.

Box 7. Six land categories

(i) *Forest Land*

This category includes all land with woody vegetation consistent with thresholds used to define Forest Land in the national greenhouse gas inventory. It also includes systems with a vegetation structure that currently fall below (but in situ could potentially reach) the threshold values used by a country to define the Forest Land category.

(ii) *Cropland*

This category includes cropped land, including rice fields, and agro-forestry systems where the vegetation structure (current or potentially) falls below the thresholds used for the Forest Land category.

Continued...

(iii) *Grassland*

This category includes rangelands and pasture land that are not considered Cropland. It also includes systems with woody vegetation and other non-grass vegetation such as herbs and brush **that fall below the threshold values used in the Forest Land category**. The category also includes all grassland from wild lands to recreational areas as well as agricultural and silvi-pastoral systems, consistent with national definitions.

(iv) *Wetlands*

This category includes areas of peat extraction and land that is covered or saturated by water for all or part of the year (such as peatlands) and **that does not fall into the Forest Land, Cropland, Grassland or Settlements categories**. It includes reservoirs as a managed subdivision and natural rivers and lakes as unmanaged subdivisions.

(v) *Settlements*

This category includes all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with national definitions.

(vi) *Other Land*

This category includes bare soil, rock, ice and all land areas that do not fall into any of the other five categories. It allows the total of identified land areas to match the national area, where data are available. If data are available, countries are encouraged to classify unmanaged lands by the above land use categories (for example, into Unmanaged Forest Land, Unmanaged Grassland, and Unmanaged Wetlands). This will improve transparency and enhance the ability to track land use conversions from specific types of unmanaged lands into the categories above.

1.2.3 Kyoto Protocol, Bali roadmap, RE(D)$_i^{+j}$

Forest carbon (C) sinks were included in the Kyoto Protocol as a mechanism to mitigate global climate change. According to the Protocol, the net sink of C arising from land use changes and forestry over the period 2008–2012 can be credited and may be considered as a reduction of GHG emissions to fulfill the reporting requirements in the international agreements of Annex I countries.

However, for developing countries, only one category of the various land use changes is eligible as mitigation action—namely, afforestation/reforestation (A/R)—that can be part of the Clean Development Mechanism (CDM), but under strict regulation. In practice, such A/R-CDM approaches have been difficult to initiate and get approved, both at the national and the international level.

Meanwhile, the losses due to tropical deforestation continued unabated. At the 13th Conference of Parties in Bali in December 2007 a "Bali Road Map" was agreed upon which contained efforts to include a new mechanism for reducing emissions from deforestation and forest degradation (REDD) in the agreements that were to define the successor of the Kyoto Protocol, at the 15th COP in Copenhagen (2009) and lead to partial agreement in Cancun (2010).

In the Kyoto Protocol, only a small subset of the issues regarding land use was recognized as mitigation action and incorporated via the A/R-CDM mechanism.

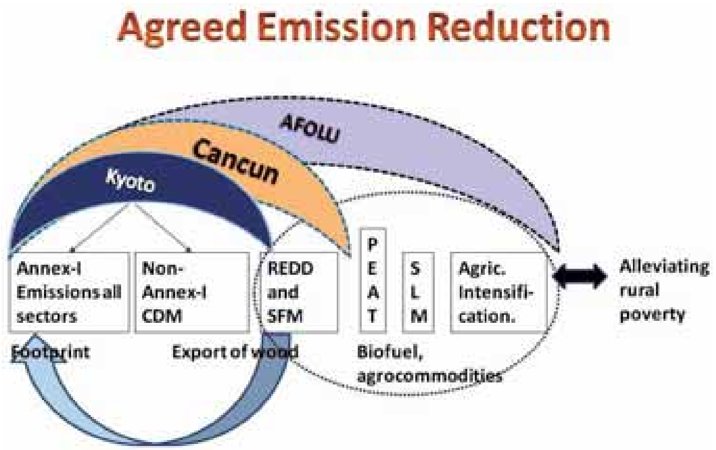

Figure 6. Components of global climate agreements required to deal with emission reduction and alleviation of rural poverty; SFM = Sustainable Forest Management, SLM = Sustainable Land Management, Agric. = Agricultural.

Current efforts on REDD and sustainable forest management (SFM) broaden the reach, but the cross-sectoral linkages in land use within the comprehensive AFOLU umbrella have probably not received enough attention (Figure 6). Forests have been singled out for priority action, but the forest definition is too fuzzy for clear delineation of what is 'in' and what is 'out'[1] (van Noordwijk and Minang, 2009).

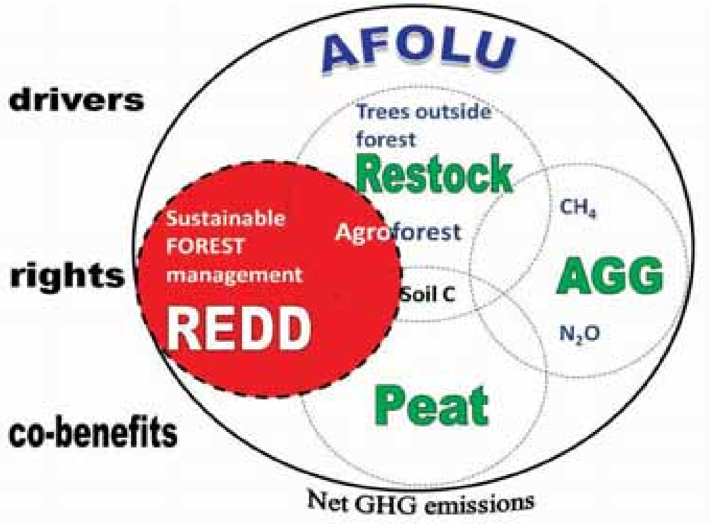

Figure 7. Relationships between REDD and other components of AFOLU (agriculture, forestry and other land uses) emissions of greenhouse gases, such as peatlands, restoring C stocks with trees and soil C and emissions of CH_4 and N_2O (agricultural greenhouse gases or AGG).

The current framing of the efforts to reduce emissions from deforestation and degradation (REDD) refers to a **partial accounting** of land use change, without clarity on **crosssectoral linkages** and **rights** other than those of forestry authorities. Negotiation processes to add safeguards will likely slow down and complicate implementation. A more compre-hensive and rights-based approach to reducing emissions from any land use, reducing emissions from any land use, (REALU), embedding REDD efforts, is likely to be more effective. This can be based on the totality of AFOLU accounting.

The progression of issues to be included in the RED → REDD → REDD+ → REDD++ (or in shorthand notation $RE(D)_i^{+j}$ for i=1,2 and j=0,1,2) is reflected in the parts of a land cover change matrix that is to be included in the calculations of emissions.

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[1] http://www.redd-monitor.org/2008/12/17/forest-definition-challenged-in-poznan/

RED	Reducing emissions from (gross) deforestation: only changes from forest to non-forest land cover types are included, and details very much depend on the operational definition of 'forest'.
REDD	REDD + (forest) degradation, or the shifts to lower C stock densities within the forest; details very much depend on the operational definition of 'forest'.
REDD+	REDD+ + restocking within and towards 'forest'; in some versions, REDD+ will also include peatland, regardless of its forest status; details still depend on the operational definition of 'forest'.
REDD++	REALU = REDD++ + all transitions in land cover that affect C storage, whether peatland or mineral soil, trees-outside-forest, agroforest, plantations or natural forest. It does not depend on the operational definition of 'forest', but on consistency in the overall land cover stratification scheme.

Definition of Forest

The forest definition accepted by the international community (Box 6) has a number of counter-intuitive consequences, such as:

A) There is no issue of deforestation in the conversion to oil palm plantations, as such plantations meet the definition of forest.

B) There is no deforestation in a country like Indonesia, as land remains under the institutional control of forest institutions and is only 'temporarily unstocked'.

C) Swiddening and shifting cultivation can be finally removed from the list of drivers of deforestation, as long as the fallow phase can be expected to reach minimum tree height and crown cover.

D) Most tree crop production and agroforestry systems do meet the minimum requirements of forest; for example, unpruned coffee can easily reach a height of 5 m.

E) The current transformation of natural forest, after rounds of logging, into fastwood plantations (Cossalter, 2003) occurs fully within the 'forest' category, out of reach of RED policies.

F) Large emissions of peatland areas that have lost forest cover and were excised from the 'forest' estate do not fall under forest-related emission prevention rules, if the conversion happened before the cut-off date (yet to be specified).

G) Substantial tree-based land cover types fall outside of the current institutional frame and jurisdiction of 'forests', and require broad-based implementation arrangements.

Probably there is no single definition of forest that can provide a clear dichotomy in the continuum of landscapes with trees. From a biodiversity perspective, a cutoff between 'natural' and 'planted' forest may seem desirable, but again there are many intermediate forms.

For issues of C accounting, definitions or terminology should not cause any fuzziness as long as a number of distinctions are made among the 'woody vegetation' components that are actually found on the land (including 'trees outside forest') and link measurements on the ground to maps that use consistent classifications. However, in terms of local and national policy, there are four broad classes of land (see Figure 8):

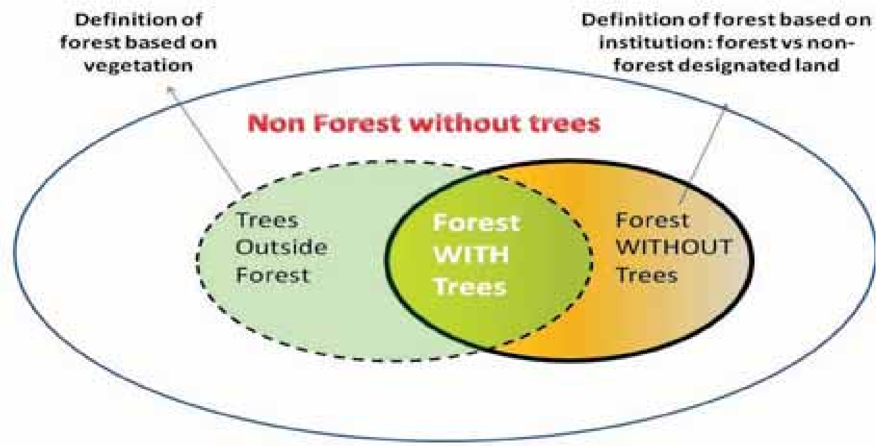


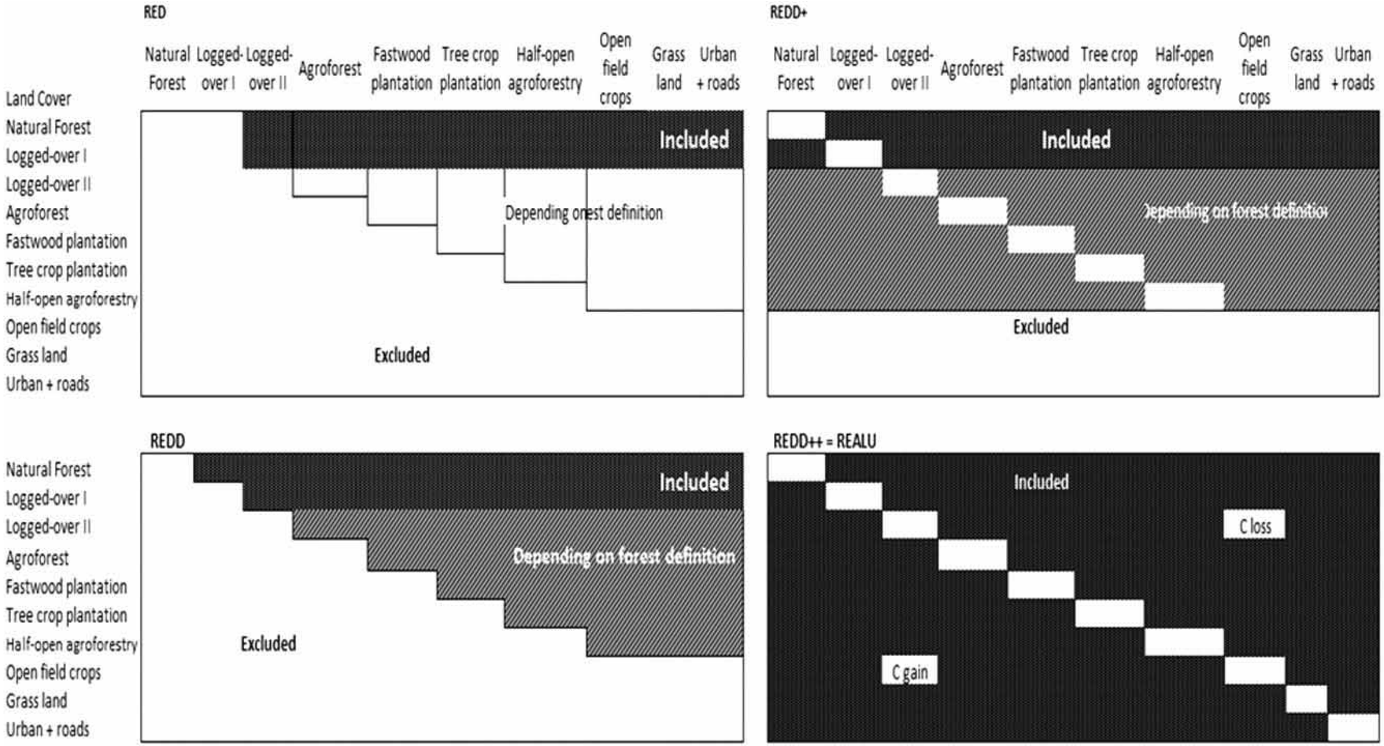
Figure 8. Four basic classes of land with respect to presence of trees and institutional forest claims.

1. Forest with trees;
2. Forest without trees, but included in the 'institutional' forest based on expectations that trees will or should be present;
3. Trees outside 'institutional' forest, above or below the threshold for tree height and crown cover;
4. Non-forest without trees.

This Manual deal with all land cover without discrimination. Terms such as 'deforestation' can be better replaced by 'changes in tree cover' or 'aboveground C stock', to avoid the policy complications of the word 'forest' and its derivatives.

The various types of REDi+j accounting schemes can now be interpreted as different ways (or filters) of processing data on land cover change. A 10-step classification of land cover can be used: 1. Natural forest; 2. Logged-over forest high density; 3. Logged-over forest medium density; 4. Agroforest (managed + natural tree establishment); 5. Fastwood plantation; 6. Tree crop plantation; 7. Half-open agroforestry, heavily logged forest and shrub; 8. Open-field crops; 9. Grassland; 10. Urban areas + roads. Adopting this classification, the parts of the change matrix can be selected that will be included in the accounting scheme for different rules (Figure 9).

Figure 9. Land use change matrix and cells (reflecting decrease or increase in C stock over a time period between two observations) that can be included in a range of possibile RED schemes.



Box 8. Forests—what's in a name?

What is a forest? What is not a forest? The history of the term ('*sylva forestis*' in Latin) suggests that it is not the equivalent of woody vegetation ('*sylva*') but rather with that part that is 'outside reach' or '*forestis*'. This qualifier became the shorthand form. Forests have always been defined by reference to an institution, for example, the king, (or 'crown') who claims control over it, not based on the presence or absence of trees. The 'king' has been replaced by 'forestry departments' of various forms in different countries, but the dichotomy between village/community and forest has usually remained. Villagers will not voluntarily describe their tree-based vegetation as a forest, as this implies a risk of denial of their rights and 'trouble'.

The forest definition agreed on by the UNFCCC in the context of the Kyoto Protocol has three significant parts, only one of which has received a lot of attention:

1) Forest refers to a country-specific choice for a threshold canopy cover (10–30%) and tree height (2–5 m); the choice of these thresholds has been widely discussed.

2) The above thresholds are applied through 'expert judgement' of 'potential to be reached *in situ*', not necessarily to the current vegetation

3) Temporarily unstocked areas remain 'forest' as long as a forester thinks they will, can or should return to tree cover conditions.

Rules 2 and 3 were added to restrict the concept of reforestation and afforestation and allow 'forest management' practices including clear felling followed by replanting to take place within the forest domain. They make the direct observation of 'forest' difficult. There is no time limit to 'temporarily'.

1.3 Measuring C stock in less uncertain ways

Estimating the carbon stock on an area can be achieved by taking a representative sample rather than measuring the carbon in all components over the whole area. A small, but carefully chosen sample can be used to represent the population. The sample reflects the characteristics of the population from which it is drawn. For carbon sampling, measurements should be accurate (close to reality for the entire population) and precise (short confidence intervals, implying low uncertainty).

1.3.1. Accuracy: bias and precision

The final value calculated from any sampling or accounting method will probably differ from the actual value at the time of assessment. While this is unavoidable, it is important to realize the consequences of inaccurate answers and the costs involved in getting better and better approximations. It is useful to distinguish between two sources of 'inaccuracy' (the difference between the estimate and the actual value)—namely, bias (systematic error) and incomplete sampling (random error)—as shown in Figure. 10. Only incomplete sampling can be dealt with by increasing the sampling effort. Bias can derive from the use of inaccurate or wrongly calibrated methods and equations, or from sampling schemes that give a higher probability of inclusion in the sample to areas with either a relatively low or a relatively high value.

The variation between replicates can be used to estimate the precision of the sample mean, but it does not reflect its accuracy, as any bias is not revealed. Bias may only show up if data from multiple sources are compared with measurements at another scale. When the first estimates of the global C cycle were made (see Figure 1), there were large amounts of 'missing carbon' due to inconsistencies in methods used by the various data sources. A number of sources of bias in the data collection have since been identified and the data gap is smaller but it still exists. In the context of policies and international regulation, bias and precision play different roles. Relative, (rather than absolute) changes in emissions and stocks are the targets of such policies. Thus, as long as bias is consistent in space and time, it does not affect the policy process. However, inconsistencies between the outcomes of different methods can be used as an excuse for inaction (”the scientists don’t yet agree, so we had better wait”). Random error tends to be smaller at a national scale of data aggregation than at sub-national units where fewer samples are involved. This is important for the scales of policy instruments. If changes in C stocks in relatively small areas are the target of a project, a substantial sampling effort will be needed to quantify those changes in C stocks for the area. If the target changes at a national scale, a similar effort spread over a much larger area might suffice to obtain the same precision at much lower cost per unit change in the C stock measured. The emphasis on precision at project scales may have contributed to the impression that C accounting at the national scale will be complicated and expensive. It does not have to be, if efficient sampling schemes are used. Political processes, however, don't readily appreciate statistical arguments, and may want to see detailed 'wall-to-wall' evidence before action is taken. The psychology and art of communication are as important as the accuracy and precision of the data.

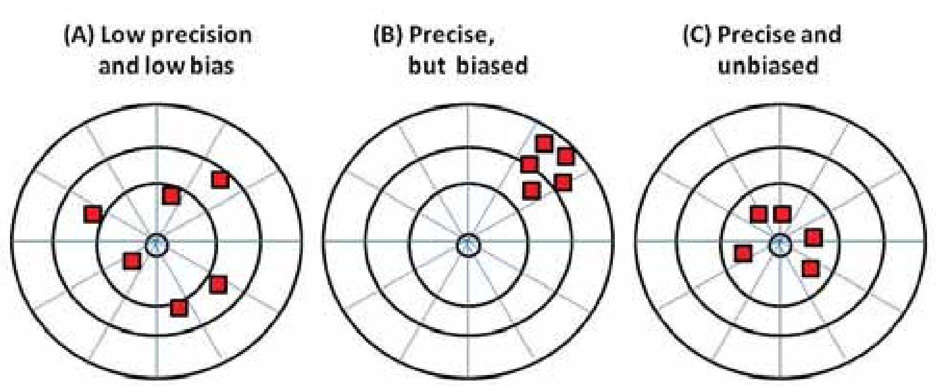


Figure 10. Lack of precision and bias can both lead to inaccurate estimates but only the first can be dealt with by increasing the number of samples. Assuming the objective is to sample the bulls eye in the centre of the target: (A) all sampling points, while close to the centre, will have low bias, but they are widely spaced and therefore have low precision; (B) all points are closely grouped indicating precision but they are far from the center and so are biased and inaccurate; (C) all points are close to the center and closely grouped, so they are precise and unbiased or in a word, accurate.

1.3.2. Stratified sampling through remote sensing

Carbon accounting makes use of stratified sampling and has the classical benefits and drawbacks of such an approach, when compared to a random sampling approach. In this case, stratification refers to the division of a heterogeneous landscape into distinct strata based on the carbon stock in the vegetation.

The benefits are:

- If the strata are well defined and internally homogeneous (relative to the total population), the number of samples required to achieve a specified accuracy of the mean is considerably smaller than with random sampling.
- This benefit is especially pronounced if relatively small strata represent high values that will be hard to correctly represent in random sampling efforts.
- The method is more robust if the overall distribution does not follow a normal probability distribution, but still assumes deviations from such a distribution within each stratum are manageable.

The weaknesses are:

- If stratum weights are not adequately known a priori or through other means, stratified sampling may be biased.
- Sampling within each stratum should still be random (equal probability for all elements in the stratum to be selected for observation), which requires mapping or listing of all stratum elements.

In carbon accounting, maps derived from remote sensing (or direct attributes at the unit or pixel scale) form the strata of a discrete number of land use/cover types. Classification errors (uncertainty of stratum weights) depend on the legend used, with generally higher precision on low carbon density landscapes and problematical distinctions within high carbon density categories, but most likely the misclassification falls within similar carbon density categories.

If the area of interest is large enough resulting in some biophysical factors that influence biomass accumulation (and therefore C stocks), such as climate and topography, not being homogeneous, then further stratification is necessary in order to reduce uncertainty. To avoid confusion, this manual refers to such stratification as zonation as opposed to stratification based on land use/cover types. Maps with appropriate scales to the extent of the area of interest are necessary to help in the design of an effective sampling procedure.

Box 9. Steps to determine the number of sampling plots (adapted from Rugnitz *et al*., 2009)

Step 1. Select the desired level of accuracy

The selection of the level of accuracy is almost always related to the resources available and the demands of the buyer (the market). The level of precision required will have a direct effect on inventory costs. Usually, the level of precision for forest projects (sampling error) is ±10% of the average carbon value with a level of confidence of 95%. Small-scale CDM forestry projects can use a precision level up to ±20% (Emmer 2007). However, specific levels of precision can be defined for each component of the inventory.

Figure 11 illustrates the relationship between the number of plots and the level (degree) of accuracy ±% of the total carbon stock in living and dead biomass, with 95% confidence limits (Noel Kempff Project in Bolivia). To achieve an accuracy level of ±5%, 452 plots are needed, whereas only 81 plots would give a ±10% level of accuracy. This example illustrates the cost-benefit implications of a higher accuracy level.

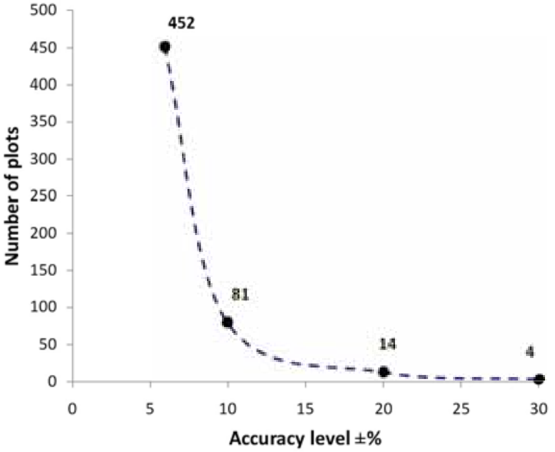


Figure 11. Relationship between number of plots and desired (or required) level of accuracy.

Continued...

Step 2. Select areas for preliminary data gathering

Before determining the number of plots required for the monitoring and measurement of carbon with a certain level of confidence, you must first obtain an estimate of the existing variance for each type of deposit (for example, soil carbon) in each land use system classified in the land use legend. Depending on the occurrence of the same stratum in the project area, each layer must be sampled over an area (repetition), so that results have statistical validity. Initially, it is recommended that a set of four to eight repetitions be used for each land use system.

Step 3. Estimating the average, standard deviation and variance of carbon stock preliminary data

The time-averaged C stock is calculated for each land use system or land use legend from the preliminary data (or obtained from the literature if studies in similar areas are available).

Output: Average, standard deviation and variance of carbon per land use system/legend.

$$\bar{x} = \frac{x_1 + x_2 + \ldots + x_n}{n} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Average

$$s^2 = \frac{\sum_{i=1}^{n}(X_i \quad \bar{X})^2}{n-1}$$

Variance

$$s = \sqrt{s^2}$$

Standart Deviation

Step 4. Calculating the required number of sampling 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:

$$n = \frac{(N * s)^2}{\frac{N^2 * E^2}{t^2} + N * s^2}$$

Continued...

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

t = statistical sample of the t distribution for a 95% level of confidence (usually a value of 2 is used)

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

s = standard deviation of the land use system

Online tools: Winrock International has developed an online Excel tool called the Winrock Terrestrial Sampling Calculator that helps in the calculation of the number of samples and the cost involved for base line studies as well as monitoring.

(See: http://www.winrock.org/ecosystems/tools.asp).

2

photo: Kurniatun Hairiah

Carbon is also stored in the necromass (dead tree) for several years at least; it will gradually be released through decomposition.

Part 2: How to do it?

2.1 Overview of Rapid Carbon Stock Appraisal (RaCSA)

The following research protocol on measuring C stocks was developed as part of the global ASB (Alternatives to Slash and Burn) project to estimate C stocks at various levels in mineral soils and peat soils. The protocol was developed as a carbon accounting tool with stakeholders under the name Rapid Carbon Stock Appraisal (RaCSA). The discussion so far has looked at national accounting systems, but the basic data for RaCSA must come from efforts at a more local level to measure the carbon stocks in the landscape. Such a more localized assessment can be undertaken by following the RaCSA protocol. The basic steps of data collection and measurement of trees are not particularly difficult and do not require expensive or complex equipment, but consistency and attention to detail are necessary. So far, much of the cost of carbon measurements has been in the design of the system and the costs for external experts to travel to remote locations rather than on the time spent actually measuring trees. Different ways of organizing these efforts can be substantially more cost effective if local expertise can be developed and standards of reporting and verification can be maintained.

With the increasing importance of carbon stock assessments in policy and the possible consequences for economic incentives (C markets), it is relevant that local stakeholders are aware of and involved in data collection and processing, so that they can deal with the ‘slick carbon cowboys’ and ‘carbon snake oil merchants’ that are exploiting the current innocence and ignorance of local governments and communities.

The RaCSA protocol includes three types of knowledge: local ecological knowledge (LEK), public/policy knowledge (PEK) and scientific/modeling knowledge (MEK) (Figure 12; Photo 1). Comparing and contrasting these knowledge types involves the classification/stratification schemes as much as the measures of carbon stock density. The public/policy domain tends to focus on institutional categories and associated departmental divisions rather than the actual vegetation and carbon stocks involved. In using existing data sources, such as 'forest cover', the lack of clarity in operational definitions used is a major problem. The main output of RaCSA is landscape carbon estimates under various scenarios of land use change, taking into account ways to measure activities that are expected to improve local livelihoods and alleviate rural poverty.

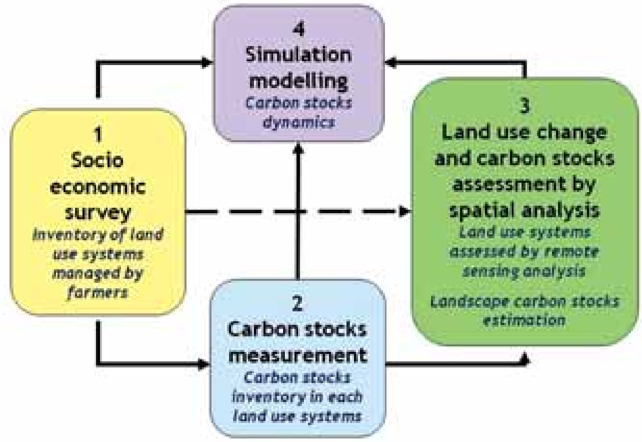


Figure 12. Four main components and outputs under RaCSA approach.

Photo 1. Inventory of all land use systems managed by farmers (1) including discussion between researchers, farmers and governments, (2, 3, 4) on the dynamics of the landscape over time as a result of changes in the way people manage their natural resources.

2.2. Concepts of carbon stock accounting and monitoring

The basis for area-based carbon stock accounting is an equation to estimate the changes in carbon stock within and between land cover classes, with each characterized as a fraction (ai) of the total area (A) (the stratum weighting) and each with a time-dependent carbon stock density $C_{i,t}$ (the stratum mean).

$$\Delta C_{t->t+1} = A_t \left(\sum_{i=1}^{n} (a_{i,t} \overbrace{(C_{i,t+1} - C_{i,t})}^{\boxed{\text{change in average C stock}}} + \overbrace{(a_{i,t+1} - a_{i,t})}^{\boxed{\text{change in area for class } i}} C_{i,t}) \right)$$

Where:

ΔC = annual change in carbon stocks in the landscape in Mg yr^{-1} or t yr$^{-1.}$

Carbon stock density consists of the aboveground and belowground biomass, above¬ground necromass and soil organic matter. The total annual change of carbon stock at the landscape level is the sum of the area of each transition of land uses multiplied by the total changes in C stock for each transition per unit area, divided by the time period. The changes accounted for are net changes, that is, the sum of gains and losses. Gains are derived from vegetation growth while losses can result from harvest, disturbance, decomposition, combustion, fertilization and drainage. When the calculations are applied to a large enough area of interest and over a long enough time period, a ‘time-averaged stock’ approach to carbon can be applied that balances the gains and losses occurring at the year-by-year level during a typical life cycle.

The choices of system boundary (landscape extent or the coverage of the area of interest) and the time period should be made based on the specific objectives of the research. The objectives should also drive the level of accuracy that is to be achieved; accuracy should not be considered independently of the level of available resources. It is important to note that the summation of the areas represents total areas, therefore this formula expresses a comprehensive accounting system rather than covering parts of the landscape, such as the natural forest only or areas designated to be a forest area. The four levels of measurement covered by RaCSA are:

- ***Tree level***: assessing the current carbon stock of an individual tree, that is, aboveground (shoot) and belowground (roots) biomass;
- ***Plot level***: estimating the current carbon stock in aboveground and belowground pools of trees and understory, in necromass (dead plant parts) and in the soil in a plot of a particular land use system;
- ***Land use system level***: calculating the time-averaged C stock of a land use system from plots of various ages within the same land use system; and
- ***Landscape level***: extrapolating the time-averaged C stocks of all land use systems to the whole landscape by integrating them with the area of land use/cover changes obtained from satellite image analysis.

2.3. RaCSA in six steps

The components of RaCSA presented in Figure 12 are further described in six practical steps (Figure 13). As mentioned above, RaCSA integrates LEK (local ecological knowledge), PEK (public/policy ecological knowledge) and MEK (scientific/modeling ecological knowledge) in the assessment and therefore its implementation requires the application of multidisciplinary skills. The assessment team should be composed of people with skills covering a multidisciplinary range—social scientists, ecologists/botanists/foresters, spatial analysts/remote sensing specialists, statisticians and modelers. In collecting and analyzing data, RaCSA uses semi-structured interviews, focus group discussions, spatial analysis using GIS and remote sensing data, landscape assessment through reconnaissance and groundtruthing, statistical analysis, field measurements and laboratory analysis.

Step 1. This is targeted to understand LEK through the identification and discovery of histories, trends and the drivers of land use and land cover changes in the study area.

Step 2. The knowledge obtained in step 1 is then reconciled and combined with the PEK and MEK to produce stratification, zonation and a lookup table of land cover, land use and land use systems. The three terms refer to different aspects of land:

- Land cover refers to vegetation types that cover the earth's surface; it is the interpretation of a satellite (digital) image of different land cover. In simple terms, it is what can be seen on a map, including water, vegetation, bare soil, and/or artificial structures.
- Land use refers to human activities (such as agriculture, forestry and building construction) at a particular location that alter land surface processes including biogeochemistry, hydrology and biodiversity; of course, the uses interact strongly with land cover, however they are not always identical: the same land cover can be used differently and the same uses can be applied to different land cover.
- Land use systems combine land cover and land use with the addition of the cycle of vegetation changes and management activities (planting and harvesting, among others); this needs more on-ground information of LEK and sometimes PEK.

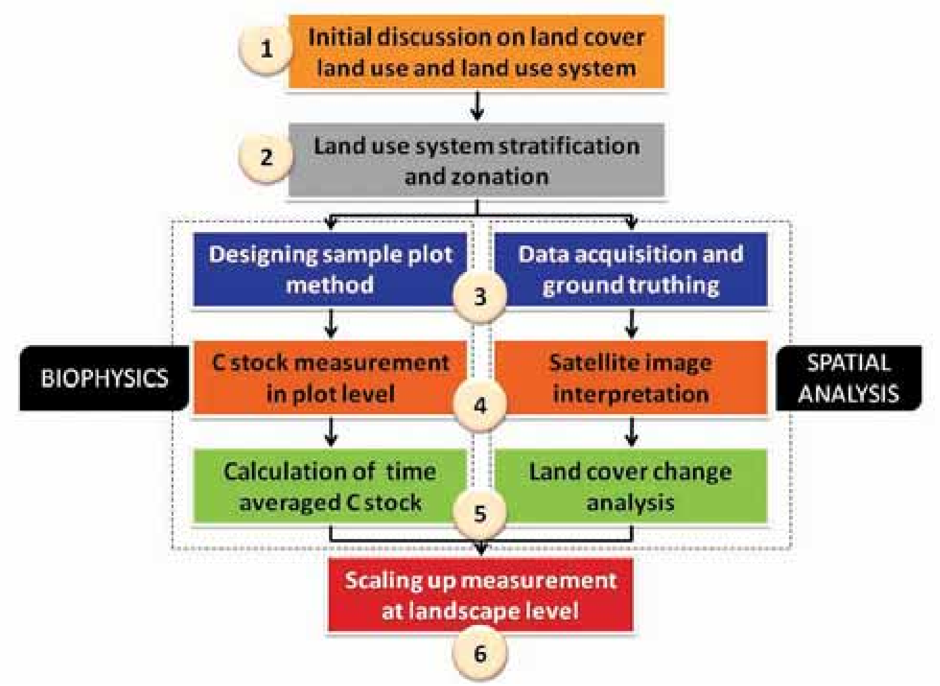


Figure 13. RaCSA in 6 practical steps

The differences among the three terms are often subtle and in some cases they converge, such as for primary forest. In many tropical parts of the world, where swidden practices and other land uses of a rotational nature are common, the land use system (LUS) approach is a key solution to address difficulties in accounting for medium timescale fluctuations of carbon stocks. LEK is the most important information source to indicate LUS, which allows for accounting of carbon stocks at the landscape level rather than partial accounting. However, when a particular LUS has not yet reached equilibrium in the landscape, such as the new trend of oil palm establishment in some areas, the age distribution of the plots can be skewed toward young vegetation so that carbon stocks can be overestimated. In such cases, calibrating the typical or time-averaged C stock into spatial-averaged C stock needs additional information on the fraction of the area in each class of the plantation in the landscape.

Beyond the second step of RaCSA, other than in the satellite image analysis, the consistent use of LUS is encouraged with the lookup table among land cover (LC), land use (LU) and land use systems (LUS) being revisited from time to time. Steps 1 and 2 are landscape level activities.

Step 3. The multidisciplinary team of MEK will discuss and determine the legend, strata or classification system based on the inputs from step 2. The legend and stratification will be used by the ecological team conducting field measurements and by the remote sensing team interpreting satellite images and producing time series maps of LU/LC.

Step 4. This step is by far the biggest step consuming most of the resources; it comprises field work to address tree and plot level activities, and desk analysis to convert the field measurement into time-averaged C stock for each LUS.

Steps 5. This is the second largest step comprising groundtruthing to collect geo-referenced information on LUS and satellite image analysis to produce time series maps of LU/LC to be linked with the LUS through the lookup table produced from step 2. Image processing is beyond the scope of this Manual; however some concepts and tips drawn from the experiences of the ASB and more recent studies will be shared here. While step 4 is described in most detail in a standardized manner, the other steps mostly involve guidelines to be used flexibly to fit the specific needs and conditions in the study area and to suit the composition of team that will conduct the C-accounting.

Step 6. This step is mostly a desk study, comprising analysis and reporting. This step integrates all levels from the tree to the landscape. For a full cycle of RaCSA, the ultimate step will be developing a simulation modeling of the carbon dynamics based on land use decision making process used by farmers. This simulation modeling part is beyond the scope of this Manual. Interested readers are encouraged to check

http://www.worldagroforestrycentre.org/af2/fallow.

Another important component deliberately left out of this Manual in order to avoid technical complexities is the uncertainty analysis of the estimates. The IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories IPCC (2000) provides a good starting point for those who are interested in delving further into uncertainty analysis. However, there is a ‘Catch 22’ in terms of discussing sampling design because deciding the number of samples to be taken is highly dependent on the level of certainty that is to be achieved. This is addressed here only by providing some guidelines to sampling design rather than prescriptive steps to calculate the number of samples.

2.4. Step 1: Local stakeholders' perspectives of the landscapes

A core aim of RaCSA is to enable the local people to gain an understanding of their landscapes, through LC, LU and LUS and to consider these as integral parts of their livelihoods by appreciating how the drivers shape and change the landscape.

Objectives:

- To overview key stakeholders and their dynamics in the study area.
- To develop a portfolio of land use, land cover and land use systems.
- To determine where, when and what land uses, land cover and land use systems are relevant and to whom, plus activities (seasonal and rotational) on site.
- To identify planned versus actual activities to reveal governance, regulation and implementation outcomes with regard to land use planning, management and land tenure.
- To identify and record historical, socioeconomic and cultural aspects.
- To identify land use changes and their drivers.
- To identify constraints to and opportunities for sustainable livelihoods.
- To document the frequency, intensity and nature of conflicts and forest fires.

Factors to consider:

- Sensitivity of land-related and forest-related issues.
- Be informative, avoid raising false expectations.
- Different terminologies from different stakeholders should be recorded.
- Non-uniform information; people tend to know better the aspects of landscapes that most directly relate to their own livelihoods.

Pre-requisite data:

- Satellite imagery/maps and/or preliminary land use/cover maps or Google Earth maps.
- Maps of road infrastructure, settlements, administrative boundaries.
- Topographic maps.

Activities:

- Interviews and/or focus group discussion with key stakeholders from government offices, academia and land managers (farmers and concession holders).

Output:

- Schematic diagram of LU, LC, LUS with regard to time horizon, land managers and government land use plans.
- Annotated maps with stakeholder information and identification of problems and opportunities.
- Documentation of interviews and FGD (farmers' group discussion).

Examples of output:

A. Schematic diagram of LU/LC, LUS dynamics (see Figure 14 for an example from Jambi, Sumatra, Indonesia). Land use/cover types are reconciled with legal land allocation in capturing the land use trajectories over time and space. For example, in this particular landscape, within forest land, primary forest is either protected as National Parks or managed for timber extraction. Following the logging activities, some logged-over forest was managed and rehabilitated as conservation areas or converted to forest plantation or coal mines. In legally convertible forest land, some logged over forest was converted to estates such as oil palm and rubber. Within the Community Forest zone and Non-forest zone, earlier in the 1900s, swidden was the most common agricultural practice; jungle rubber is an integral part of the swidden rotation but lately as swidden is not very common anymore, some jungle rubber areas have been converted to more intensive uses such as oil palm and monoculture rubber.

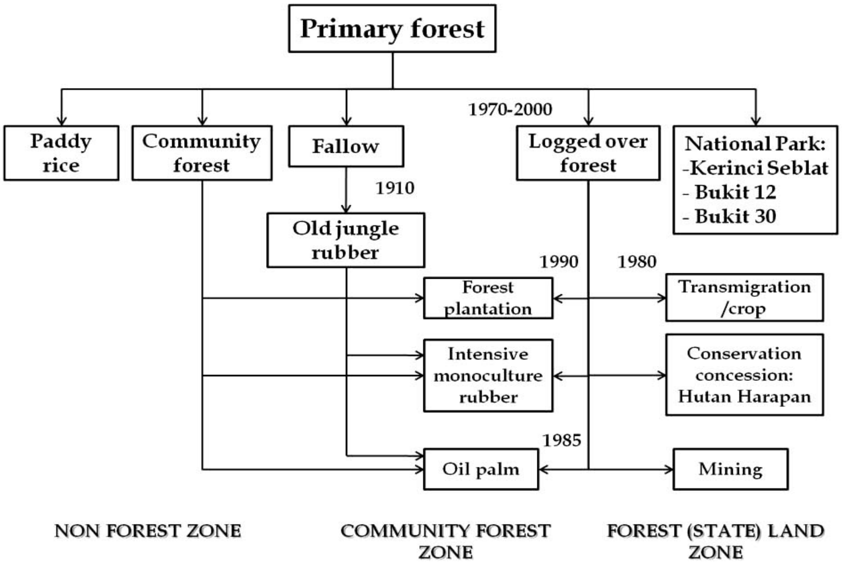
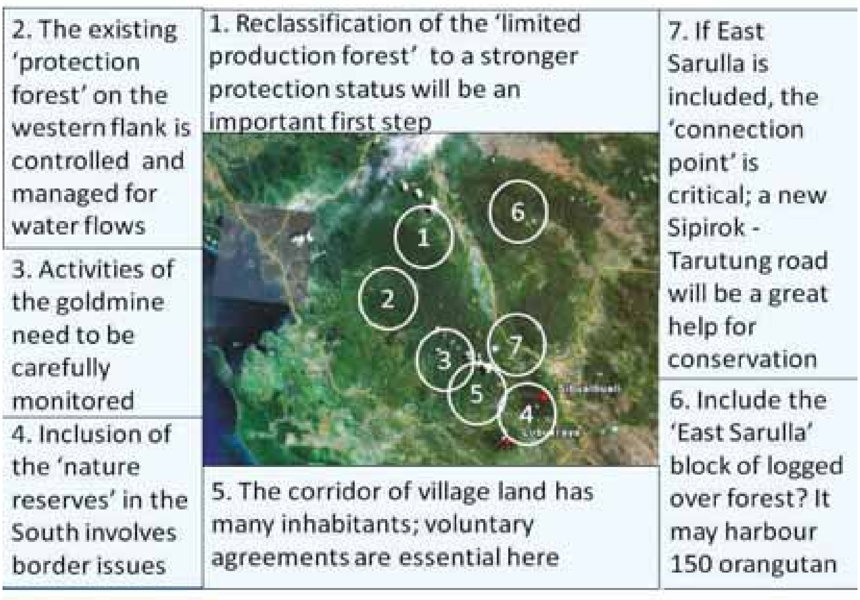


Figure 14. Schematic diagram of LU/LC and LUS dynamics in Jambi, Sumatra, Indonesia, derived from a focus group discussion exercise.

B. Annotated map of Batang Toru, Sumatra, Indonesia (Figure 15). Using a crude map as a base map, local stakeholders and their interactions in the landscape were identified and mapped. The early scoping process of problems and opportunities through mapping and interviews with key informants was very rewarding. For example, there was identification and mapping of: the portfolio of land use/cover types; land managers and issues; areas of biodiversity hotspots and watershed protection; and potential threats.



2. The existing 'protection forest' on the western flank is controlled and managed for water flows

3. Activities of the goldmine need to be carefully monitored

4. Inclusion of the 'nature reserves' in the South involves border issues

1. Reclassification of the 'limited production forest' to a stronger protection status will be an important first step

5. The corridor of village land has many inhabitants; voluntary agreements are essential here

7. If East Sarulla is included, the 'connection point' is critical; a new Sipirok - Tarutung road will be a great help for conservation

6. Include the 'East Sarulla' block of logged over forest? It may harbour 150 orangutan

Figure 15. Annotated map of Batang Toru, Sumatra, Indonesia from interviews with key informants (Note: This step is a subset of the DriLUC (Drivers of Land Use Change) tool developed by ICRAF - see http://www.worldagroforestrycentre.org/sea/projects/tulsea/inrmtools/DriLUC).

2.5. Step 2: Zoning, developing lookup tables between LC, LU and LUS and reconciling LEK, MEK, PEK in representing landscapes for C stock assessment/deciding on legend/classification scheme

The process used to disaggregate the total area into classes of land cover and zones can make a substantial difference to the final estimates as well as affecting the certainty level of the estimate. There are several aspects to consider in producing a meaningful classification and stratification/zonation scheme to account for C stocks in the landscape. Three main factors are: (a) vegetation cover/land cover, (b) abiotic factors that affect the productivity and species composition, such as elevation, climate, soil, land form, geology and (c) anthropogenic factors that affect biomass removal, species composition, growth, and induce disturbances.

The following example show how splitting the areas into different classes regarding land cover can make a substantial difference to the C stock estimates. In areas where mosaics of core primary forest and degraded logged over forest are marked, lumping the two types of land use systems into one category, (for example, forest) and substituting the time-averaged C stock of undisturbed forest into the whole area classified as forest will result in a huge overestimation of C stocks or an underestimation of C emissions. The results of the Jambi study (Tomich *et al*., 1998) can be used to illustrate this problem *et al*. (see Figure 16). The time-averaged C stock of the undisturbed natural forest was 450 Mg ha^{-1} while for the degraded forest it was 175 Mg ha^{-1}. If the differences are disregarded and the forest land use system is assigned to both (450 Mg ha^{-1} C stock) including some areas that are actually degraded, logged over forest, then the result will be a large overestimate. There needs to be sufficient distinction within the forest category that results in units that are reasonably uniform in their properties.

Lumping together peatland and mineral soil that have similar land cover is an example of how an abiotic factor can influence the C stock estimates. In peatland areas, the biggest portion of the C stock is stored belowground rather than aboveground. Therefore ignoring this and substituting the time-

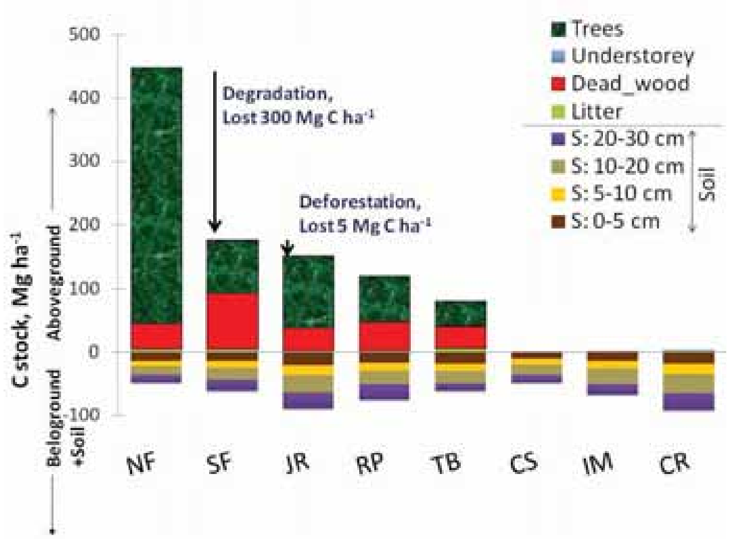


Figure 16. Measurements of five C pools (trees, understory, dead wood, litter and soil) in various land use systems of Jambi; the data still need conversion to time-averaged C stock over the system's life cycle (Tomich *et al*., 1998).

averaged C stock of soil from the mineral soil into the peatland areas will cause a substantial underestimation of the total C stock.

Management types are important parameters, which often cannot be seen directly from the satellite imagery. However, with some auxiliary data such as base maps, proxies, policies and regulations, and an understanding of the drivers, local context and local land use practices, the management types and intensities might be represented spatially and used as a stratification/zonation layer. Some examples are boundaries of gazetted forest uses, areas of swidden agriculture and logging concessions.

In summary, the choice for the types of land cover to be distinguished in a particular study, need to be based on:

- A meaningful classification scheme for capturing C stock variation; the units should be homogeneous in key properties and between them, they should cover all land use types.
- Stratification and zonation based on abiotic (such as soils and climatic zones) and anthropogenic factors (accessibility classes).
- Landscape level patterns that are replicated, for example, toposequences in watersheds.

- Source of data: combination of local ecological knowledge and base maps.
- Links with participatory mapping exercises and existing spatial data.

Where possible, nested or hierarchical classification systems should be used that allow zooming in and out in the data analysis stage.

Box 10. Understanding and representing landscapes: determining the classification scheme, stratification and zones

The IPCC guidelines (2006) suggest categorization of land uses into 6 types: Forest Land, Cropland, Grassland, Wetland, Settlement and Other Land (see Box 5 for more detail). These classes may reflect institutional history and interests but in many cases the categories are problematic and do not appropriately represent intermediate land use types, such as between Forest Land and Cropland with trees for agroforestry systems or between Cropland and Wetland fir rubber agroforests on peat domes. The available statistics need to be scrutinized for the operational definitions used and the gaps and overlaps between categories identified. As discussed, the ‘forest land’ definition adopted globally and used in many countries does not guarantee the presence of trees at any point in time.

2.5.1. Zonation

Objective:

- To identify factors that affect the amounts of C stock and the dynamics given the same vegetation type/land cover.

Factors to consider:

- Ranges of relevant abiotic factors that potentially can cause variation in the particular landscape of interests in terms of the C stock for similar land cover.

- Local land use practices and sets of rules and regulations that potentially can cause variations in the management of types of land which result in variation in the C stock for similar land cover.
- Disturbance histories and potential.
- Availability and accuracy of secondary data and information .
- Limiting resources only allow an optimal number of strata and zones.

Pre-requisite data:

- Maps of land systems and suitability (including rainfall, temperature, landform, geology, soil, among others) of appropriate scale.
- Maps of boundaries of gazetted land uses, such as areas designated for production forest, for protection forest and for non-forest uses.

Activities:

- Literature review of the variation in abitotic and management types in and surrounding the area of interest.
- Interviews with key informants (in three categories: government officials, academics, and community and other land managers such as logging concessioners, estate companies) at the landscape and sub-landscape levels of variation in abiotic and management types in the landscape which affect C stock levels. Disturbance histories and probability should be discussed. Cross-checking the maps collected prior to the discussions with the key informants should be very useful in assessing the quality of the maps and identifying the gaps between actual practices and the regulations. Information on the availability of maps at a larger scale that are more up-to-date and accurate should be gathered actively during the discussions.
- Collection, compilation and assessment of the relevant maps.
- Technical assessment of which strata/zones are feasible with the available maps and technical discussion between spatial analysts and ecologists/ biologists in the team on optimal strata and zones. The principle to be followed is that the stratification/zonation scheme should capture differences in C stock of similar land cover types.

Output:

- Lists of strata/zones and maps.

Examples of abiotic factors that potentially can be used as zones:

- Elevation: how to decide on the classes with different systems followed for agricultural practices from those of forestry, for example, in agriculture, the threshold is 700 m above sea level, in forestry, the threshold is 1000 m or 2000 m above sea level.
- Rainfall: similar approach as above.
- Land systems.
- Soil and geology (Figure 17).

Examples of management factors:

- Gazettal of forest land
- Drivers and trends (Figure 17)

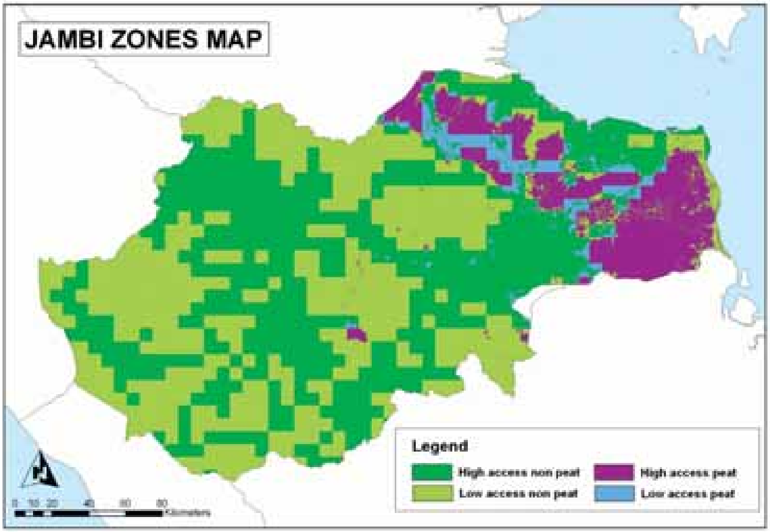


Figure 17. Map of zonation of Jambi, Sumatra based on combination between soil types (peat and non peat) and accessibility (high and low).

2.5.2. Reconciling LEK, MEK, PEK perspectives on landscape representations

Objectives:

- To capture different perspectives of landscape representation from LEK, MEK and PEK.
- To reconcile the perspectives in an optimal way that is recognizable from remote sensing techniques within an allowable error level, with the C stock estimate sensitive from an ecological perspective and reflective of the on-the-ground uses and contexts.

Factors to consider:

- Spatial and spectral resolution of satellite imagery to be used.
- Spatial variation of the study area.
- Technical skills.
- Portfolio of LUS: complexities of LU/LC, length of rotation.
- The configuration and composition of each LUS.
- There are accuracy trade-offs between LU/LC mapping and estimation of the C stock of LUS.

Pre-requisite data:

- Schematic diagram of LU, LC, LUS with regard to time horizon, land managers and government land use plan.
- Annotated maps.
- Base maps at three scales (small scale map covering an area larger than area of interest, medium scale map covering exactly the area of interest, large scale map covering subset of the area of interest, presumably covering the ‘hotspots/specific’ interests, such as areas with specific histories of land use practices, burnt areas, areas of peculiar abiotic characteristics).

Activities:

- Preliminary exploration of image analysis, using spectral signatures of each suggested LU, LC, LUS produced from Step 1.
- Discussion among key informants (slicing into three categories: government personnel, academics and communities, and other land managers such as logging concessioners, estate companies), ecological team and remote sensing team to develop explicit descriptions of uses and management activities, especially those that affect biomass gain and loss, in each land cover in different areas in the landscapes. A lookup table should be filled and linked to the maps. The actual LC, LU, LUS and other factors such as abiotic variation, drivers and management types that influences land cover and therefore shapes the landscape should be covered.
- Technical assessment of what actual land cover and use portfolio types found in the landscape can be recognized from the specific satellite imageries of choice, taking into account consideration of the trade-offs between going into a very detailed classification scheme while losing accuracy or an intermediate scheme with higher accuracy associated with the products. The principle to be followed is that the land cover schemes should capture differences in C stock, and be C stock sensitive.

Output:

- Several alternatives of classification schemes to be explored, which are structured hierarchically to allow efficiency in the technical work.
- Lookup table between LC, LU, LUS.

Example of Vegetation types that are C stock sensitive:

a. Natural Forest: undisturbed, low logging intensity, high logging intensity.

b. Swamp forest or mangrove: undisturbed, low logging intensity, high logging intensity.

c. Timber tree-based system (monoculture): teak, sengon, acacia, eucalypt, mahogany, rubber.

d. Non-timber tree-based system (monoculture): oil palm, coconut, horticulture.

e. Mixed/multistrata tree-based system dominated by non-timber: coffee, cocoa, coconut.

f. Mixed/multistrata tree-based system dominated by timber species: rubber, teak.

g. Mixed/multistrata system: no dominant species.

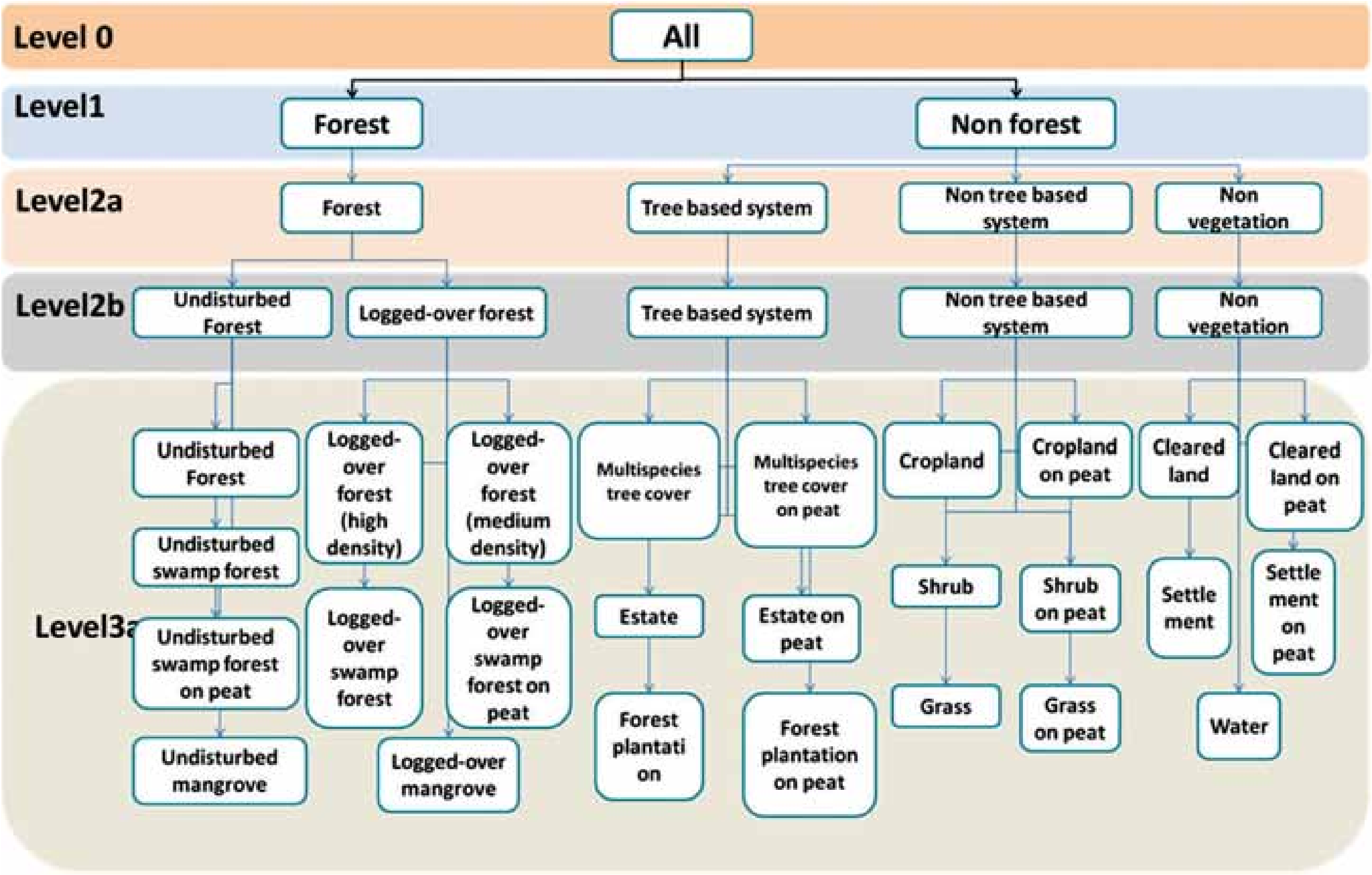
h. Bush/fallow: dominated by non-woody vegetation.

i. Grassland: imperata, savanna.

j. Bare land.

k. Settlement.

Figure 18. Hierarchical classification scheme of land cover for Jambi, Sumatra, Indonesia.



2.6. Step 3: Stratification, sampling design and groundtruthing scheming

Referring to earlier discussion (Part I, section 1.2), stratified sampling rather than fully randomized sampling is proposed. The selection of a legend of land cover classes that can be used for strata weights as well as C stock density measurements in a consistent way is a key step in the process, where much of the quality of the final product is determined. Within a hierarchical scheme, the higher levels can be generic and applied globally, while the lower levels are adjusted to the types of land use and the terms used locally.

Objective:

- To reduce the uncertainty of the estimates of the time-averaged C stock in each land use systems of different strata/zones.

Factors to consider:

- Number of strata/zones, land use systems, land cover types.
- Extent of area of interest.
- Spatial representativeness.
- Accessibility across the landscape.
- Targeted level of certainty/accuracy or allowable level of uncertainty/error of estimates.
- Limiting resources only allows some optimal number of strata and zones and replications in the plot measurement for each land use system.

Pre-requisite data:

- List of land cover types, lookup table between land cover types and land use systems, list of strata/zones.
- Overall budget of the project, costs of field measurements (including cost of moving from one plot to another) and laboratory costs.

- Prior knowledge of standard deviation of time-averaged C stock for each LUS of each zone.

Activities:

- Decide on how many plots are feasible with the current budget level and allowable level of uncertainty, when the standard deviation of time-averaged C stock for each LUS of each zone is known. If it is unknown, then estimation from secondary data or expert judgement will be an alternative. Readers should consult a sampling textbook.
- Prioritize land use systems and strata/zones to be covered based on their area dominance in the landscape (area-proportional sampling), the significance of amount of C stock and C stock dynamics and the likely variations among land use system × strata/zones (purposive sampling).

- Using the maps, randomly select the locations for each of the land use systems × strata/zones. Select a larger set of locations than the planned number of plots to be measured in order to provide alternatives. This is to prepare for some surprises people might find in the field, such as completely inaccessible areas.
- Identify the most efficient routes to reach the sample plots, since in most cases involving forested areas, accessibility is poor and therefore the cost of moving from one place to another within the study area can be high.

Output:

- List of locations (coordinates) of suggested plot samples under each land use systems × strata/zones (see example in Figure 19).

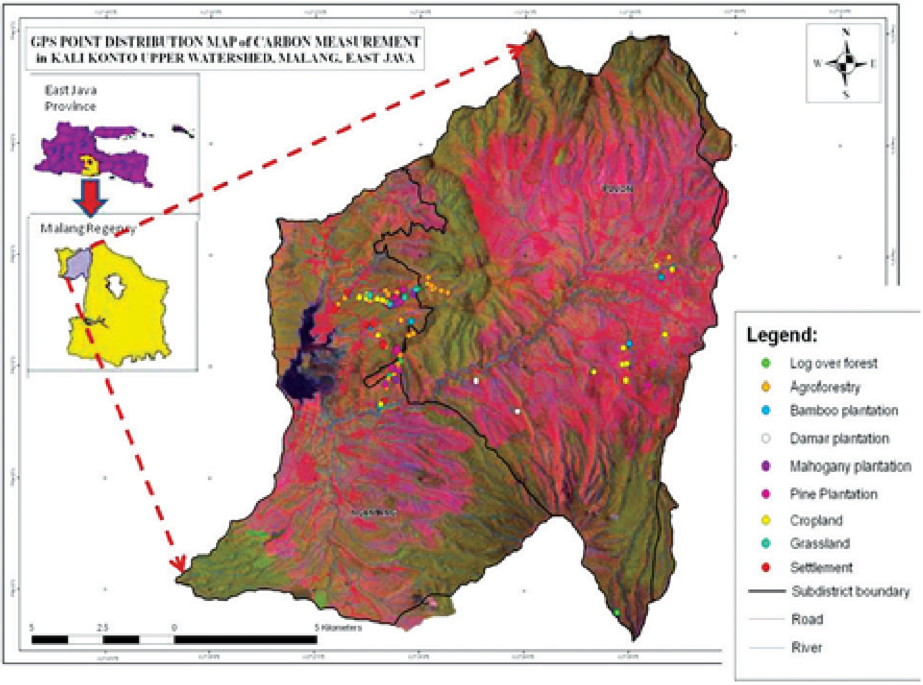


Figure 19. Map showing location of all plots selected for carbon measurements in Kalikonto watershed

2.7. Step 4: Field measurement, allometry modeling, plot level C, time - averaged C stock

This step provides a comprehensive coverage of the field protocol and the subsequent analysis, which are detailed and in chronological order so that the readers can easily follow the step-by-step procedures. The field data collection embraces the plot level and tree level. At the plot level, the two most important data to be collected accurately are: plot history, (especially the age of current plot) and the location coordinates of the plot. Plot age is important in order to derive the time-averaged C stock of LUS and is collected by interviewing either the owner or knowledgeable people in the area. The plot location coordinates recorded using a GPS receiver are important in order to match field measurements with the spatial data. Apart from errors in the plot-level estimates, inaccuracies can derive from the link between plot samples and the life cycle of the system, with its inherent variability in cycle length.

This section will discuss in detail six blocks of activities that cover all carbon pools as required by IPCC, starting from setting up the plot. On the plot, measurements are made of trees (diameter, species identification) and other aboveground biomass (living and dead) and of the belowground organic pool. Through allometric modeling and laboratory analysis, these measurements can be converted to C stock for each component which when combined add up to the total C stock at the plot level and is then scalable to the C stock per unit area (hectare). What then remains to be done is to calculate the time-averaged C stock for each LUS which is represented by replicates of plots of different ages.

2.7.1. Setting up a plot sample

Nested sampling plots of variable sizes adjusted to the C pool sampled are used along with methods to estimate the tree size from stem diameter (and height) and destructive sampling of soil and necromass. Before commencing the measurement of target parameters, subplot samples should be set up in each selected plot with three considerations:

- For forest land generally two rectangular plots (5 m × 40 m = 200 m^2) are selected within a plot of at least 1 ha, avoiding the boundary of the plot, unless specifically indicated in the sample design (see Photo 2). The geoposition of each plot should be recorded using a GPS.
- Rectangular plots are chosen as they tend to include more of the within-plot heterogeneity, and thus be more representative than square or circular plots of the same area. The larger the total area sampled, the more accurate the estimate reflects the actual condition. Instead of sampling a large, contiguous area, it is better to divide the sampling into several, smaller areas within the field of study (randomly chosen or based on some a priori stratification).
- Plot location is randomized if there are marked discontinuities in the vegetation. In other words, be sure that the plots do not only fall in areas with the densest or least vegetation.

Photo 2 (A) Setting up rectangular subplots for measurement in natural forest (A1, A2, A3) and in agroforestry systems

Photo 2. (B) (B1,B2,B3), geo-position of each plot should be recorded using GPS.

Procedure

- Set out two 200 m^2 quadrats (5 m × 40 m), by running a 40 m line through the area, then sampling the trees > 5 cm diameter that are within 2.5 m of each side of the tape (Figure 20), by checking their distance to the center line.
- If trees with diameter > 30 cm are present in the sampling plot, whether or not they are included in the transect, an additional sample plot of 20 × 100 m is needed, including all trees with a diameter > 30 cm.
- For a plantation system with low population density in the range 300–900 tree/ha, set out 500 m^2 quadrats (20 m × 25 m) instead of 200 m^2.

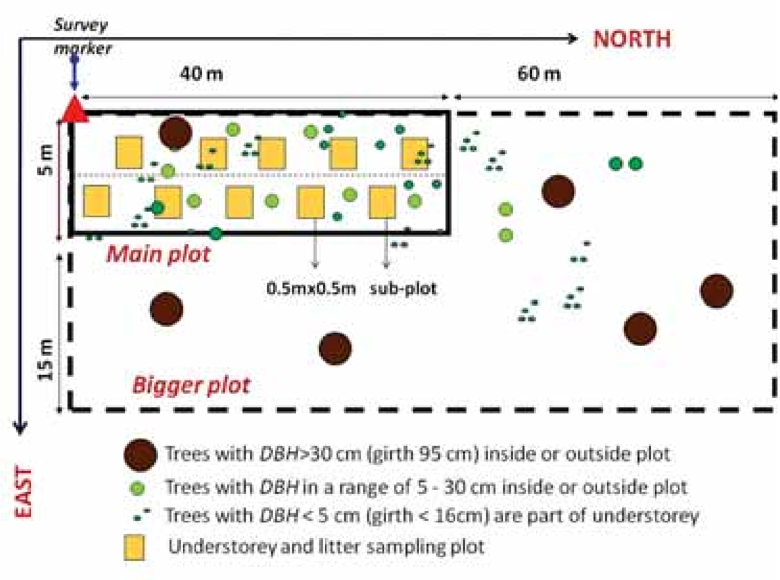


Figure 20. Diagram of nested plot design for sampling in forest and agricultural ecosystem.

This non destructive method is rapid and a much larger area and number of trees can be sampled, reducing the sampling error encountered with the destructive method. Yet, half of the biomass of a natural forest can be in the few trees of the largest diameter class (> 50 cm) and sampling error is still high for a 200 m^2 transect which can have 0, 1 or 2 large trees included (Table 1). Accuracy would be improved if trees with a DBH above say 30 cm could be sampled in a 20 m × 100 m sampling area. After a slash-and-burn event or forest fire, the remaining charred trees, branches and litter can be measured following the same protocol.

Table 1. Expected number of trees in sample plots of different size.

Diameter (cm)	Average number per ha	Expected number per plot	
		2 x (5 m × 40 m)	20 m × 100 m
5 to 10	400	16	-
10 to 30	200	8	-
30 to 50	50	2	10
50 to 70	10	0.4	2
> 70	4	0.1	1

2.7.2 Measuring living plant biomass carbon

Aboveground plant biomass comprises all woody stems, branches and leaves of living trees, creepers, climbers and epiphytes as well as understory plants and herbaceous growth. Belowground biomass comprises roots, soil fauna and the microbial community.

Trees sequester and store large amounts of carbon in their aboveground (trunks, branches, leaves) and belowground (roots) biomass. Measuring the C stock of a tree should start by measuring tree biomass, followed by analyzing its carbon content. The carbon stock of a single tree can be estimated by multiplying the carbon content conversion factor (use a default value of 0.46) by the tree biomass.

DBH large trees tend to have large roots too. For mixed tropical forest, the ratio of aboveground to belowground biomass is approximately 4:1; in very wet conditions, the ratio can shift upwards to 10:1, while under dry conditions it may decrease to 1:1 (van Noordwijk *et al*., 1996, Houghton *et al*., 2001; Achard *et al*., 2002; Ramankutty *et al*., 2007 *et al*.).

Equipment for Tree Measurement

1. Measuring tape for center of transect, 50 m long
2. Plastic rope lengths of 40 m and 5 m for setting up observation subplots
3. Sticks 2.5 m long to measure plot width
4. Wooden sticks 1.3 m long to measure stem height for DBH measurment
5. Diameter tape (d-tape) sold by forestry supply companies which includes the factor for conversion to diameter, or girth tape
6. Caliper for measuring diameter on small-sized trees
7. Knife
8. Tree height measurement device (e.g. ‘Haga meter’, optional)
9. Marker pen
10. Work sheets
11. GPS
12. Compass

2.7.2.1 . Aboveground biomass

Assessment of aboveground tree biomass can be undertaken non-destructively using allometric biomass regression equations. An estimate of the vegetation biomass can provide 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 uneven-aged stands, as 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 large sample area by destructive sampling and some form of allometry is used to estimate the biomass of individual trees using an easily measured property such as stem diameter.

Procedure

- Measure the stem diameter of each tree (within a 40 × 5 m subplot) at 1.3 m above the soil surface using a diameter tape (d-tape). If a d-tape is not available on the site, a girth tape can be used as well but the measured girth must be converted to a diameter. Tree diameter at breast height is commonly abbreviated to *DBH*. For small- or medium-sized trees, measuring the diameter using calipers is easier and quicker than using a girth tape.
- The stem girth measurement (in cm)has to be converted to a diameter (d, in cm) using the following formula:

  $$d = \text{Girth}/\pi \;, \quad (\pi = 3.14)$$

- Record the botanical species or local name of each tree as this can help improve the estimates of wood density.
- Record all measurements within the transect on worksheet 1A for big trees (*DBH* >30 cm) and worksheet 1B for small trees (5 cm < *DBH* ≤ 30 cm).

CAUTION:

- Biased measurement results are common if measurements are not taken at breast height (1.3 m above the soil surface).
- Keep the d-tape level and tight around the tree and at a right angle to the tree axis (see photos 3, 4 and 5), pulling the tape taut. Do not let the tape droop low on the back side of the tree as it will result in an overestimate. Bark may fall off the stem between consecutive measurements and produce considerable measurement errors.

Photo 3. Measurement of tree diameter: (1) Normal tree in natural forest; (2) stem branching before 1.3 m; and (3) measuring diameter and height of coconut tree in agroforestry ecosystem.

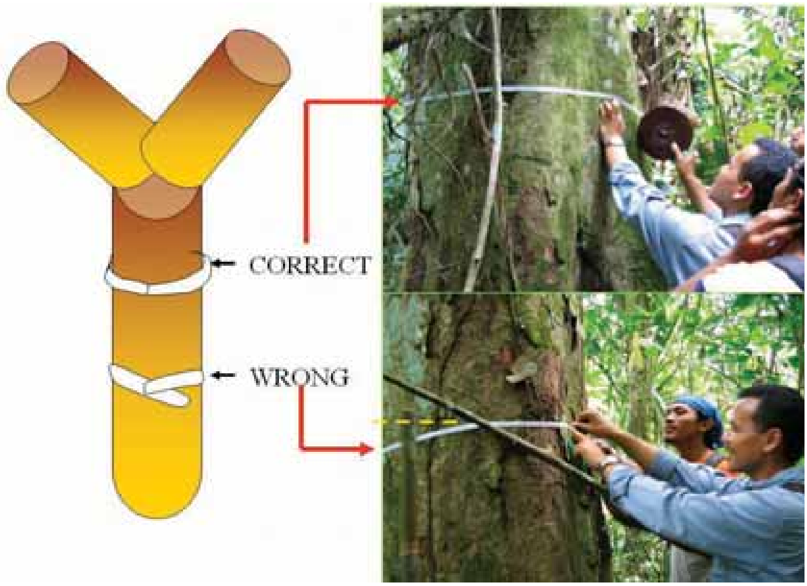


Photo 4. Measuring tree diameter using girth tape. Do not let the tape sag as it must be placed at right angles to the stem of the tree.

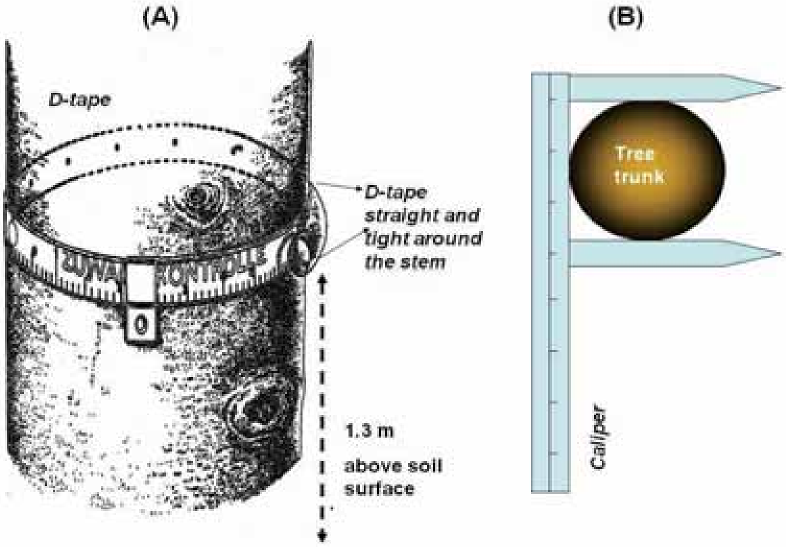


Photo 5. Diagram of measuring smaller tree diameter using d-tape (A) and caliper (B). Keep caliper horizontal around the tree, repeat the measurement from a different angle to reduce bias due to uneven surface on stem (copied from Weyerhaeuser and Tennigkeit, 2000).

2.7.2.2. Measuring the diameter of an abnormal tree

For trees with a clear, gradually tapering trunk, measuring the DBH is straightforward. However, there are a number of circumstances, such as irregular tree diameters, leaning trees and trees with plank roots, where the question arises of how best to measure the *DBH* (Photo 6). Figure 21 provides a schematic guide to solve some of the more common complications.

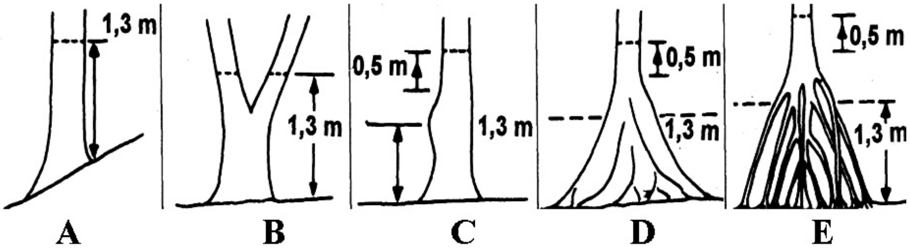


Figure 21. Guide for determining DBH for abnormal trees (Weyerhaeuser and Tennigkeit, 2000).

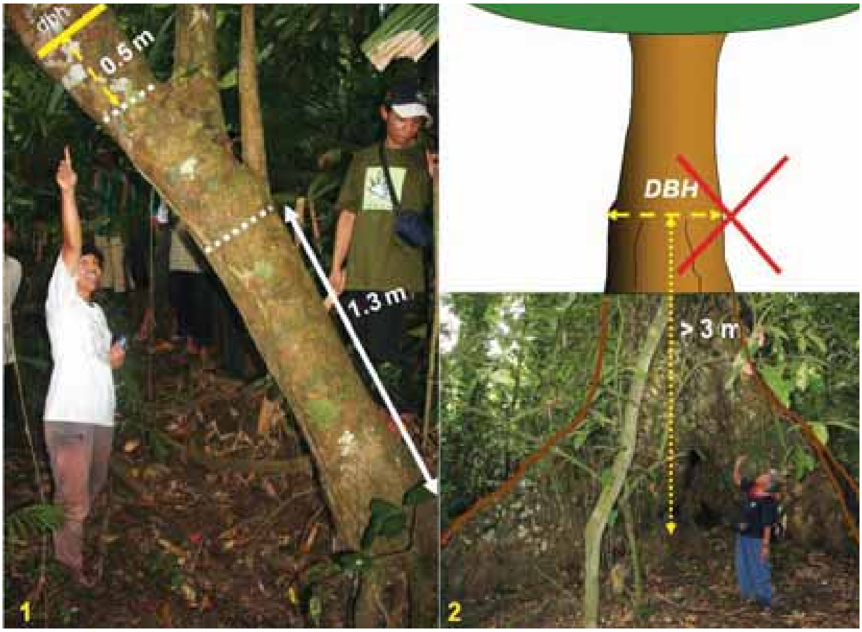


Photo 6. Tree leans and branches after 1.3 m. The measurement should be made at the smoothest part of the main stem, at 0.5 m after the branch. (2) Big trees with plank roots are often found in tropical forests, how to measure tree diameter of this big tree? Do not climb the tree: See Box 8!

Box 11. Estimating diameter on a tree with a high root plank

1. Measure the length of your arm (L1, m), see schematic graph (Figure 22).

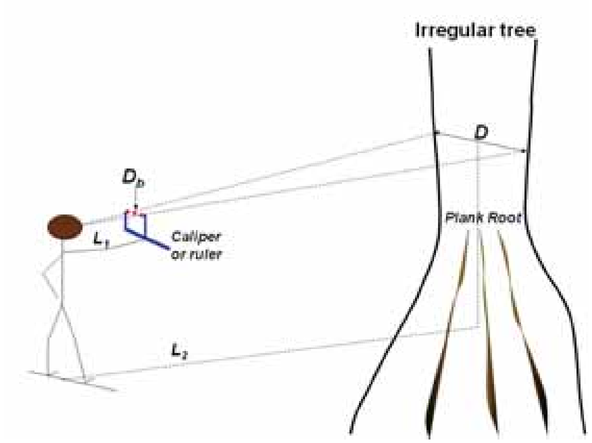


Figure 22. Schematic diagram showing how to measure the diameter of a big tree with plank roots based on a geometric approach.

2. Stand 10 m away from the trunk (L2, m).
3. Hold the ruler in the upright vertical position from your eye, measure the tree diameter (stem width) of tree trunk above the root plank (D, m), read the corresponding measurement off the ruler (Db, cm).
4. Calculate tree diameter using the following formula:

$$D\ (m) = \frac{D_b \times L_2}{L_1}$$

2.7.2.3. How to convert tree measurement data to aboveground biomass

Forest inventories are most useful to evaluate the magnitude of carbon fluxes between aboveground forest ecosystems and the atmosphere. Guidelines have been published for establishing permanent plots, characterizing trees correctly and for estimating aboveground biomass (Brown, 1997; Gibbs *et al*., 2007). Tree biomass can be estimated using allometric equation for specific tree species. Tree allometry establishes quantitative relations between some key characteristic dimensions of the tree which are usually fairly easy to measure (such as tree diameter and height) and other properties that are often more difficult to assess (biomass). However one of the largest sources of uncertainty is the lack of standard models using allometric equations to convert tree measurements to aboveground biomass. This has resulted mainly because of the very large diversity of trees species and variety of tree ages (related to diameter) growing in a tropical forest, so it is not possible to use only one specific regression model as can often be done in the temperate zone (Brown, 1997). Furthermore, direct tree harvest data (especially from big trees) are very limited, so it is impossible to independently assess the model's quality.

Allometric equations can be locally developed by destructive sampling, or derived from the literature for supposedly comparable forest types. The equations developed by Brown (1997) are based on diameter (D) at breast height (1.3 m) and the height of the tree (H) and have been used widely in the tropics. Separate equations have been developed for tropical forests in different annual rainfall regimes: dry < 1500mm; moist 1500-4000mm; and wet > 4000mm. For the humid tropics, however, using the generic allometric equation developed by Brown (1997) resulted in an overestimate (double the correct amount). Using tree-specific allometrics that include estimates of wood density lead to lower biomass estimates, especially in the low-to-medium biomasss categories (van Noordwijk *et al*., 2002). A critical reassessment of the quality of models across tropical forests and agroforestry types performed by Chave *et al*. (2005) suggested that the most important predictors of aboveground biomass (AGB) of a tree were, in decreasing order of importance, its trunk diameter, wood specific gravity, total height and forest type (dry, moist or wet). Separate equations that have been developed for tropical forests and agroforestry are presented in Table 2, while the estimation of the biomass of trees which have been regularly pruned or trees from monocotile families such as the coconut tree and oil palm are presented in Table 3.

Table 2. Allometric equation for estimating biomass (kg per tree) from tree diameter 5–60 cm of different life zones (Chave *et al*., 2005).

Life zone (rainfall, mm/yr)	Allometric Equation
Dry (<1500)	1. $(AGB)_{est} = 0.112 \ (rD^2H)^{0.916}$ 2. $(AGB)_{est} = \rho * \exp(-0.667+1.784 \ln(D)+0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)$
Humid/ moist **(1500–4000)**	1. $(AGB)_{est} = 0.0509 \ x \ \rho D^2H$ 2. $(AGB)_{est} = \rho * \ \exp(-1.499+2.148 \ln(D)+0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)$
Wet (>4000)	1. $(AGB)_{est} = 0.0776 * (\rho D^2H)^{0.94}$ 2. $(AGB)_{est} = \rho \ * \ \exp(-1.239 + 1.980 \ln(D)+0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)$

Note: (AGB)est = Estimated aboveground tree biomass, kg/tree; D = DBH, diameter at breast height, cm; H = tree height, m; r = Wood density, g cm^{-3}, ρ = Wood specific gravity, Mg m^{-3}. (available from: http://www.worldagroforestry.org/sea/Products/AFDbases/AF/index.asp).

Model Validity

- These regression models are valid only for broadleaf trees with stem diameters in the range 5–156 cm and tree biomass in the range 50 g – 1 t.
- These equations should NOT be used beyond their range of validity. Estimation of the biomass of conifer tree species, palms, lianas, and the bamboo family should use separately established equations.

Table 3. Allometric equations for estimating biomass (kg per tree) from trees with regular pruning (coffee and cacao) and trees from monocotile families such as palm trees (coconut and oil palm) and bamboo as well as other crops (banana).

Tree species	Allometric equation	Source
Coffee regularly pruned	$(AGB)_{est} = 0.281\ D^{2.06}$	Arifin, 2001
Cacao	$(AGB)_{est} = 0.1208\ D^{1.98}$	Yuliasmara, 2008
Oil palm	$(AGB)_{est} = 0.0976\ H + 0.0706$	ICRAF, 2009
Palm	$(AGB)_{est} = \exp\{-2.134 + 2.530 \times \ln(D)\}$	Brown, 1997
	$(AGB)_{est} = 4.5 + 7.7 \times H$	Frangi and Lugo, 1985
Bamboo	$(AGB)_{est} = 0.131\ D^{2.28}$	Priyadarsini, 2000
Banana	$(AGB)_{est} = 0.030\ D^{2.13}$	Arifin, 2001

Note: (AGB)est = Estimated aboveground tree biomass, kg/tree; D = DBH, diameter at breast height, cm; H = tree height, m; r = Wood density, gcm^{-3},ρ = Wood specific gravity, Mg m^{-3}. (available from: http://www.worldagroforestry.org/sea/Products/AFDbases/AF/index.asp).

Box 12. Regression models for estimating aboveground tree biomass

Trees hold large stores of C, but great uncertainty remains regarding their quantitative contribution to the global C cycle. Regression models are used to estimate the aboveground tree biomass (ABG) grown in a natural forest or in agroforestry system, such as developed by Ketterings *et al*. (2001):

$$Y = a \rho D^b$$

Where: a = intercept Y; b= power coefficient; ρ = wood specific gravity (g cm^{-3}); D = diameter at breast height DBH (cm).

Analysis using data from various allometric equations developed by Waterloo (1995), Siregar and Dharmawan (2000), Ketterings *et al*. (2001), Zianis and Mencuccini (2004) Chave *et al*. (2005) and Santos (2005) shows that the above allometric equation has one, rather than two

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degrees of freedom, as the a and the b parameters are strongly linked (Figure 23).

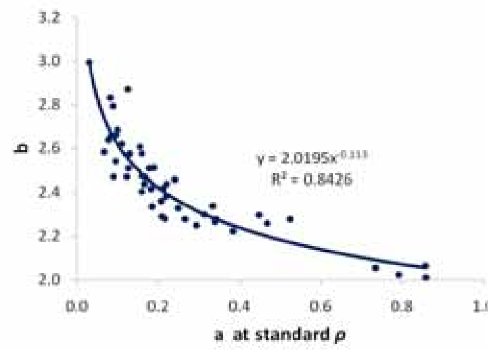

Figure 23. Empirical relationship between a (intercept) and b (power coefficient) of published allometric relations of aboveground tree biomass, after correcting the a parameter for wood specific gravity (ρ).

When the empirical linkage between the a and b parameters is used (Figure 23), the different equations show a minimal difference for a tree diameter of approximately 30 cm; equations with a low power coefficient yield relatively high biomass estimates in the lower diameter range, but relatively low ones in the higher diameter range, and vice versa. If the equations are applied to a forest stand, rather than a tree, the results have a low dependence on the specific allometric equation chosen if the majority of tree diameters are < 30 cm but some reach up to 50 or 60 cm. Only if trees > 60 cm diameter are present will the choice of equation have a substantial effect. Unfortunately, site-specific allometric equations for the local forest giants can only be secured by destructive sampling of all the big trees – in which case the data will refer to natural history and not current reality. Some uncertainty in the final estimate must be accepted.

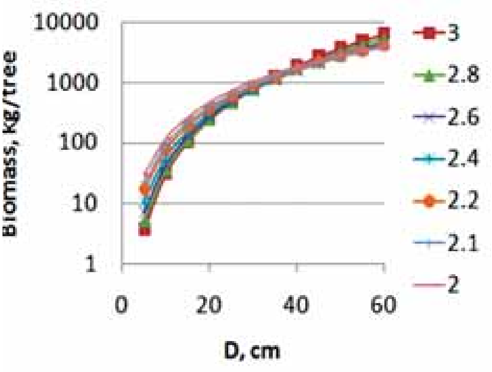

Figure 24. Relationship between stem diameter and tree biomass for allometric relations for different b parameters, in which the a and b parameters are linked as indicated in Figure 23.

2.7.2.4 Estimating tree root biomass

Large trees tend to have large roots which are an important part of the C cycle because they transfer large amounts of C directly into soil where it may be stored for a long time. For rapid appraisals use default ratios appropriate for the climatic zone, as discussed before. If these assumptions need to be verified, allometric equations based on proximal root diamaters need to be developed (van Noordwijk and Mulia, 2002).

2.7.3. Measuring Carbon at plot level

In forest and agricultural ecosystems, C is mainly stored in the plant biomass (aboveground and belowground) and in the soil. The aboveground biomass comprises all woody stems, branches and leaves of living trees, creepers, climbers and epiphytes as well as understory plants and herbaceous undergrowth (see Photo 7). For agricultural land, this includes crops and weed biomass. The dead organic matter pool (necromass) includes dead fallen trees, other coarse woody debris, litter and charcoal (or partially charred organic matter) above the soil surface. The carbon stock of litterfall in a tropical rain forest is typically about 10 Mg ha^{-1} yr^{-1}, with a mean residence time in the litter layer of about 1 year. Dead trees may take about 10 years to decompose, and the necromass is about 10% of total aboveground carbon stock in a healthy natural forest. Logging tends to focus on the more valuable trees, damaging many others. After logging, the necromass may be 30–40% of the aboveground carbon stock. If fire is used in land clearing, the C in this necromass will be emitted to the atmosphere, otherwise it may take a decade to decay.

Some measurements of the three pools of carbon stock at the plot level are described in Table 4, which are the same as described in the IPCC guidelines (IPCC, 2006) and consist of three steps:

- Assessment of biomass. The biomass measured includes trees and understory (herbaceous) biomass. Aboveground biomass can be measured destructively for annual crops or grasses or for the understory. Tree biomass can be measured non-destructively using allometric biomass regression equations as described in section 2.7.2. Below-ground biomass (roots) can be estimated using a default value (Chave *et al*., 2007).

- Assessment of necromass. Destructive assessment is possible for litter remaining on the soil surface or the assessment can be non-destructive for dead wood.
- Assessment of soil organic matter. Determination of this source of C has to be carried out in the laboratory.

Table 4. Aboveground measurements and methods used in C stock measurement.

Measurement	Method
Biomass	
• **Aboveground biomass of living trees**	Non-destructive, apply allometric equation
• **Understory/ herbaceous**	Destructive
• **Belowground biomass (roots)**	Non-destructive, using default value (Cairns *et al*., 1997; Mokany *et al*., 2006)
Necromass	
• **Dead standing trees**	Non-destructive, apply equation for volume of cylinder (for branched and unbranched remains)
• **Dead felled trees**	Non-destructive, apply equation for volume of cylinder (or allometric equation)
• **Stump (trunk) remains on forest**	Non-destructive, apply equation for volume of cylinder
• **Litter (coarse/ standing litter, fine litter, surface roots**	Destructive sampling
Soil Organic Matter	Destructive sampling followed by laboratory analysis

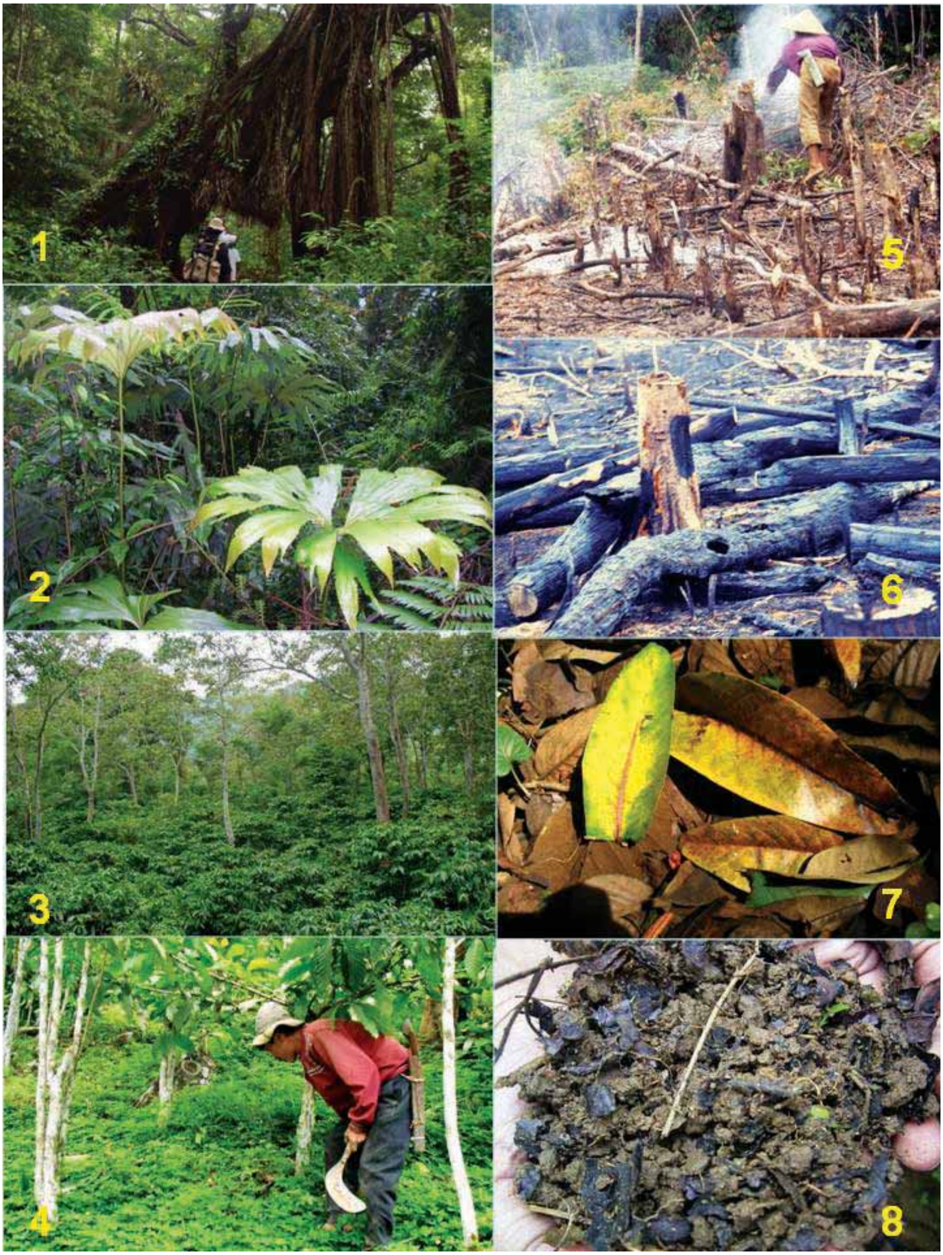

Photo 7. Carbon stored in living biomass comprises all tree biomass and understory plants in a forest ecosystem (1 and 2) and in biomass and herbaceous undergrowth in an agroforestry system (3 and 4). The dead organic matter pool (necromass) includes dead fallen trees, other coarse burned wood and woody debris, litter and charcoal (5–8).