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

Measuring Carbon Stocks

Across Land Use Systems

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

Citation

Hairiah K, Dewi S, Agus F, Velarde S, Ekadinata A, Rahayu S and van Noordwijk M, 2010. Measuring Carbon Stocks Across Land Use Systems: A Manual. Bogor, Indonesia. World Agroforestry Centre (ICRAF), SEA Regional Office, 155 pages.

This Manual has been published in close cooperation with Brawijaya University (Malang, Indonesia) and ICALRRD (Indonesian Center for Agricultural Land Resources Research and Development).

Disclaimer and Copyright

ISBN 978-979-3198-55-2

Contact details

Kurniatun Hairiah (kurniatunhairiah@gmail.com) and
Sonya Dewi (s.dewi@cgiar.org)

World Agroforestry Centre
ICRAF Southeast Asia Regional Office
Jl. CIFOR, Situ Gede, Sindang Barang
PO Box 161, Bogor 16001, Indonesia
Tel: +62 251 8625415
Fax: +62 251 8625416
www.worldagroforestrycentre.org/sea

Photo on front cover

Kurniatun Hairiah dan Daud Pateda

Design and layout

Sadewa (sadewa@cgiar.org)

This Manual is an update from the 2001 “Alternatives to Slash and Burn” lecture notes:

Hairiah,K., Sitompul, SM, van Noordwijk, M. and Palm, C.A., 2001 Carbon stocks of tropical land use systems as part of the global C balance: Effects of forest conversion and options for ‘clean development’ activities. ASB_LN 4A.

And

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

Published as parts of:

van Noordwijk, M, Williams, S.E. and Verbist, B. (Eds.) 2001. Towards integrated natural resource management in forest margins of the humid tropics: local action and global concerns. ASB-Lecture Notes 1–12. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia. And available from: http://www.icraf.cgiar.org/sea/Training/Materials/ASB-TM/ASB-ICRAFSEA-LN.htm

The practical guide published in Bahasa Indonesia is an additional associated publication.

Hairiah K and Rahayu S. 2007. Petunjuk praktis Pengukuran karbon tersimpan di berbagai macam penggunaan lahan. World Agroforestry Centre, ICRAF Southeast Asia. ISBN 979-3198-35-4. 77pp.

Hairiah K, Ekadinata A, Sari R R, Rahayu S. 2011. Petunjuk praktis Pengukuran cadangan karbon dari tingkat plot ke tingkat bentang lahan. Edisi ke 2. World Agroforestry Centre, ICRAF Southeast Asia and University of Brawijaya (UB), Malang, Indonesia ISBN 978-979-3198-53-8. 90 pp.

Content

Table of Figures

Table of Photographs

Table of Tables

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

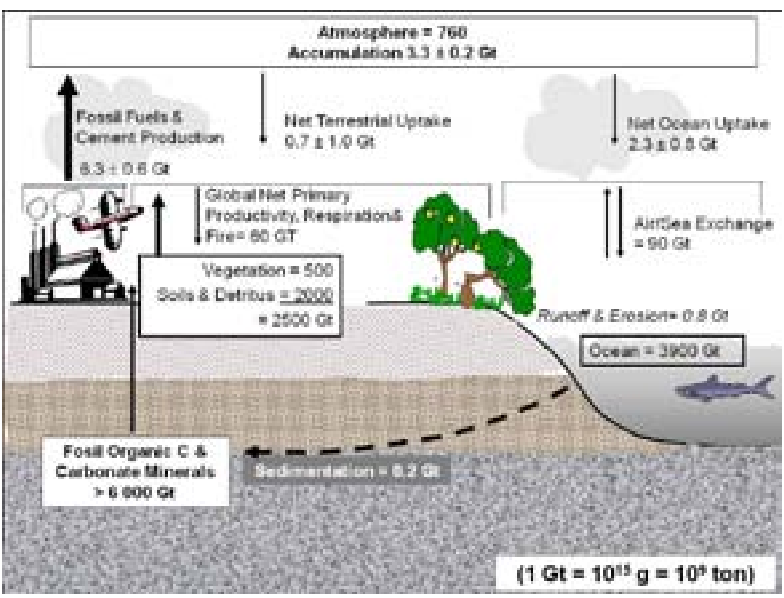


Figure 1. The global C-cycle showing the C stocks in reservoirs (in Gt = 10^{15}g = 10^9 tonne) and C flows (in Gt yr^{-1}) relevant to anthropogenic disturbance, as annual averages over the decade from 1989 to 1998 (based on Schimel *et al.*, 1996, cited in Ciais *et al.*, 2000).

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'.

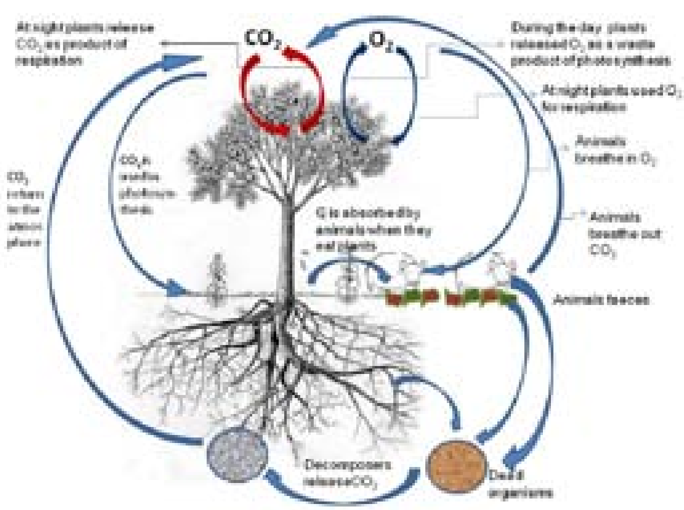


Figure 2.   Illustration of carbon cycle at plot level (quoted from http://www.energex.com.au/switched_on/being_green/being_green_carbon.html).

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).

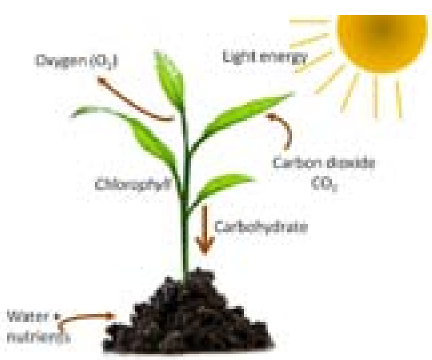


Figure 3. Photosynthesis diagram (available from: http://bioweb.uwlax.edu/bio203/s2008/brooks)

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:

$$\text{Glucose} + \text{Oxygen} \rightarrow \text{Energy} + \text{Water} + \text{Carbon Dioxide}$$

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)

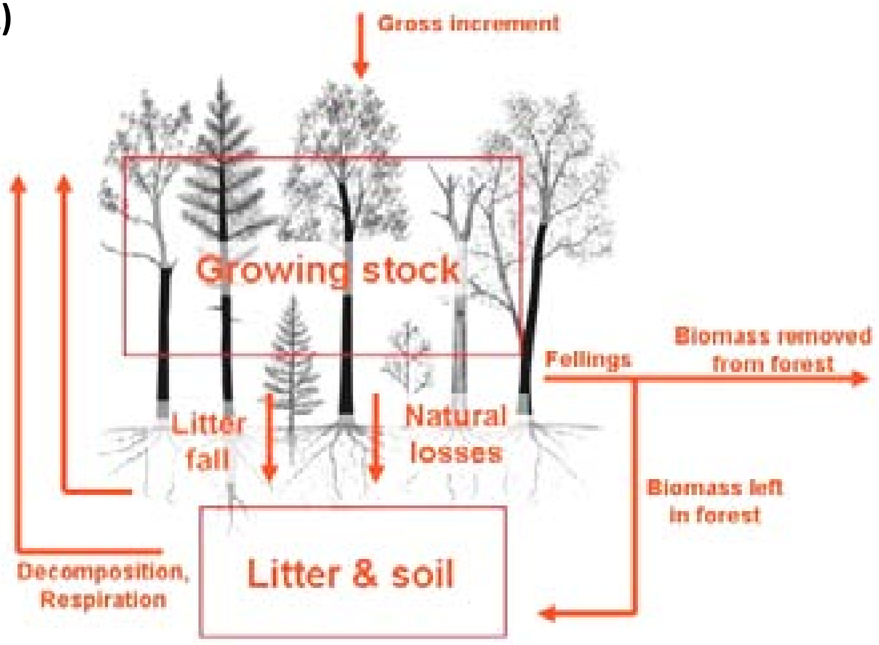


Figure 4. (A) Illustration of forest inventory-based approach to estimate carbon budgets, where estimates of stem volume of growing stock, gross increment and fellings are converted to biomass, which is further converted to litterfall with turnover rates and the estimated litterfall is fed into dynamic 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);

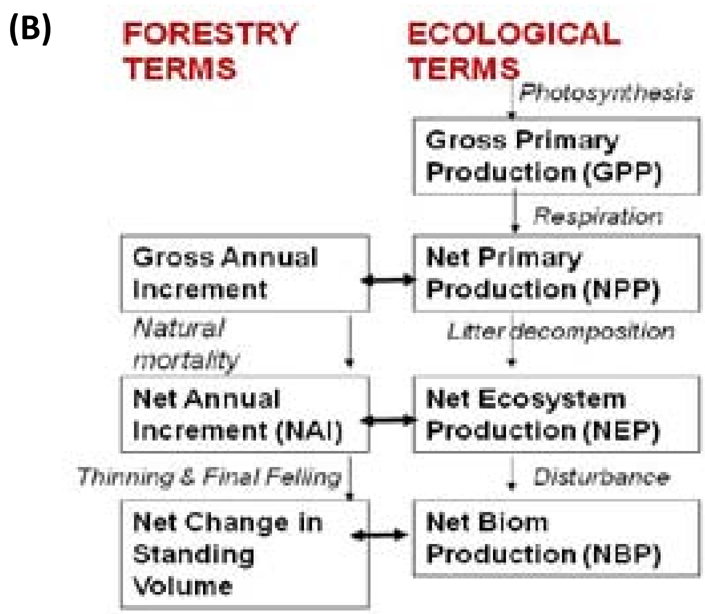


Figure 4. (B) Equivalent terms as used in Forestry and Ecological research.

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).

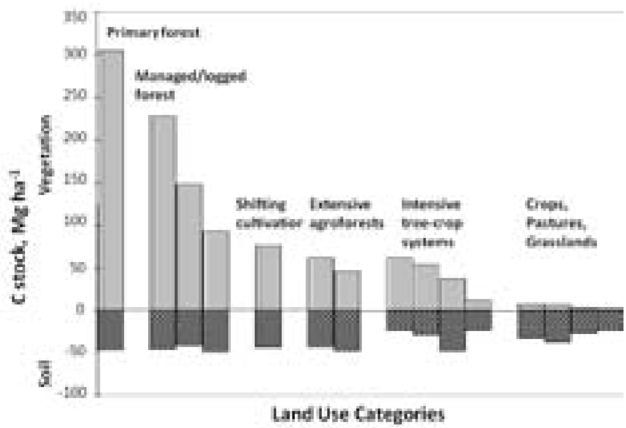


Figure 5. Aboveground time-averaged carbon stocks and total soil C (0–20 cm) for land uses in benchmark sites in Indonesia, Cameroon and Brazil. Details of data collection are explained in Part 2.

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.

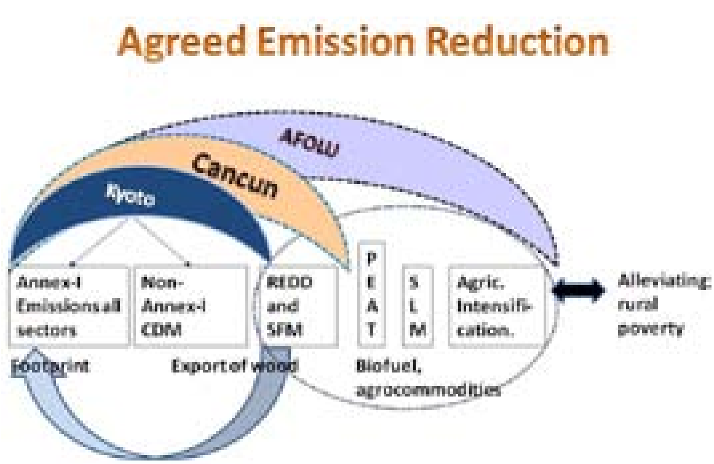


Figure 6. Components of global climate agreements required to deal with emission reduction and alleviation of rural poverty; SFM = Sustainable Forest Management, SLM = Sustainable Land Management, Agric. = Agricultural.

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).

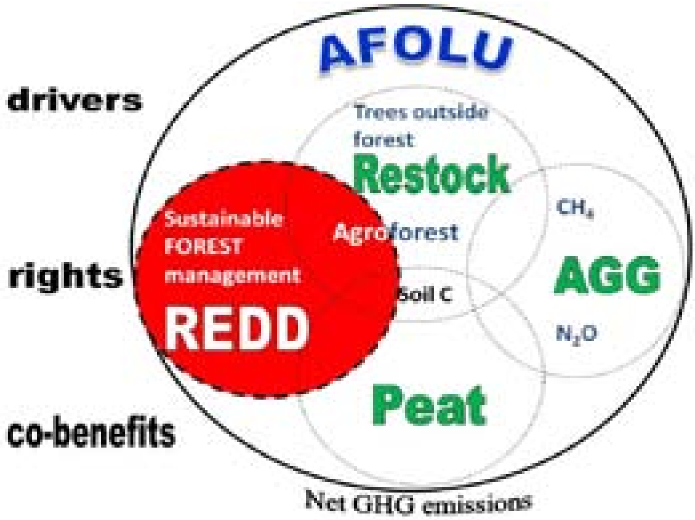


Figure 7. Relationships between REDD and other components of AFOLU (agriculture, forestry and other land uses) emissions of greenhouse gases, such as peatlands, restoring C stocks with trees and soil C and emissions of CH_4 and N_2O (agricultural greenhouse gases or AGG).

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 **cross-sec¬to-ral 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.

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):

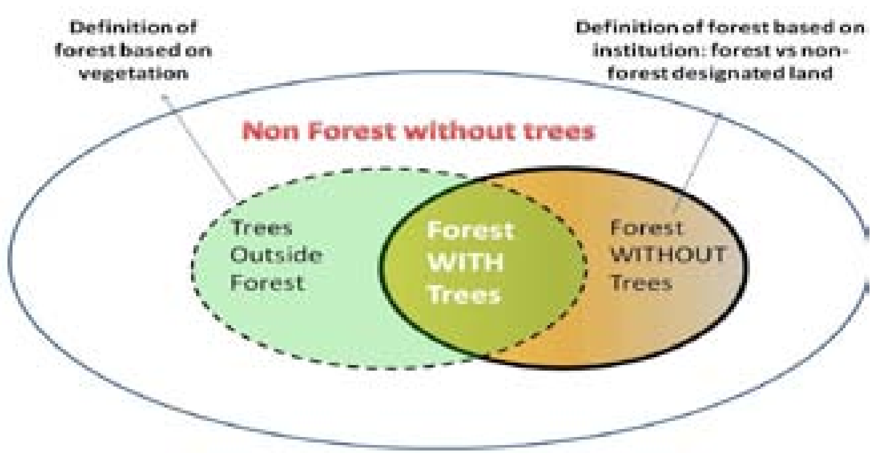


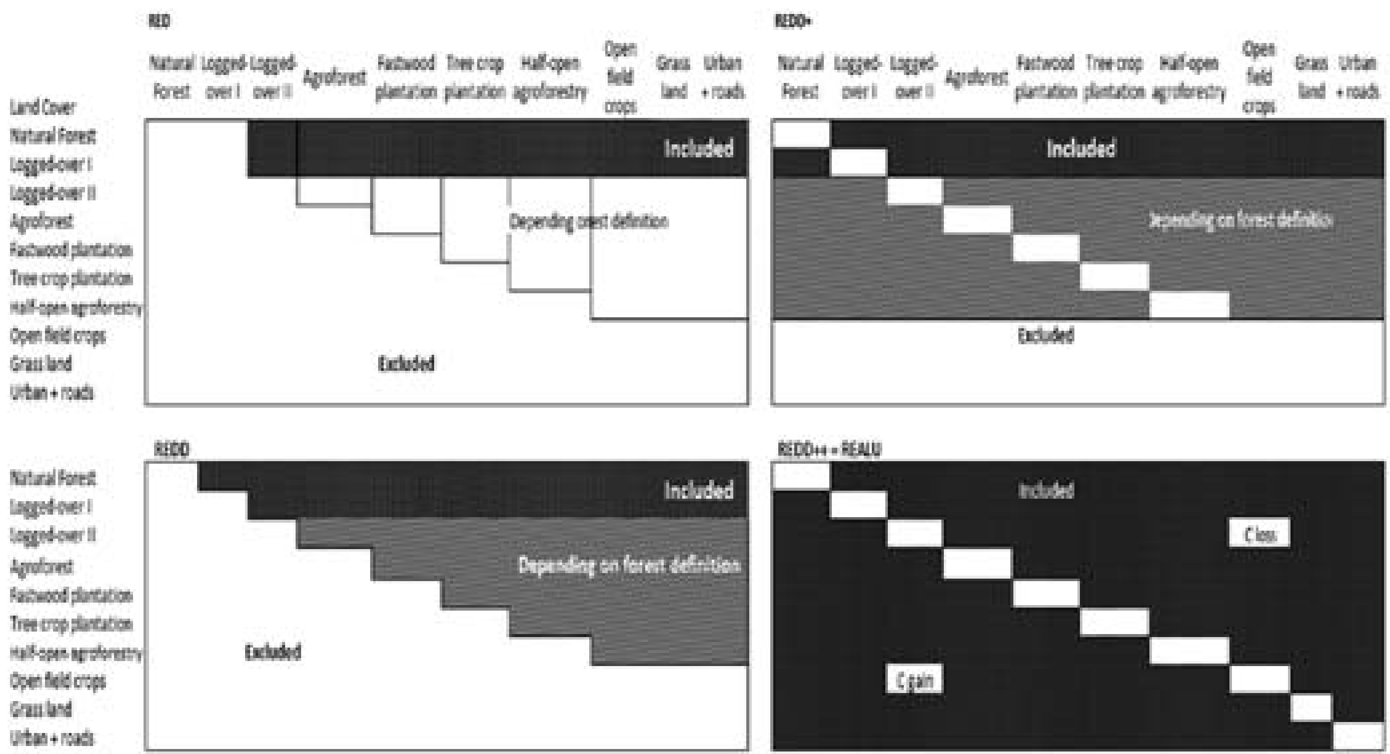
Figure 8. Four basic classes of land with respect to presence of trees and institutional forest claims.

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.

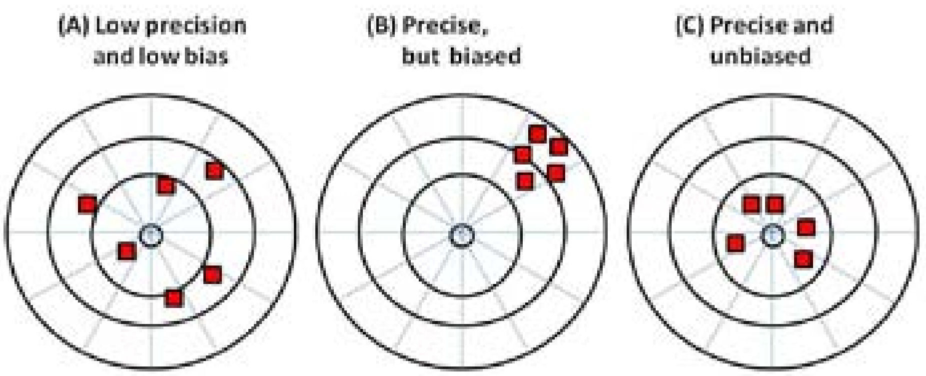


Figure 10. Lack of precision and bias can both lead to inaccurate estimates but only the first can be dealt with by increasing the number of samples. Assuming the objective is to sample the bulls eye in the centre of the target: (A) all sampling points, while close to the centre, will have low bias, 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.

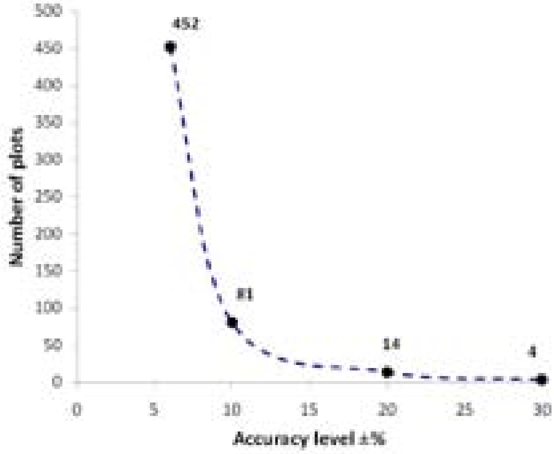


Figure 11. Relationship between number of plots and desired (or required) level of accuracy.

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.

$$\bar{X} = \frac{X_1 + X_2 + \ldots + X_n}{n} = \frac{\sum_{i=1}^{n} X_i}{n} \qquad S^2 = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1} \qquad S = \sqrt{S^2}$$

Average Variance 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).

Measuring Carbon Stocks

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.

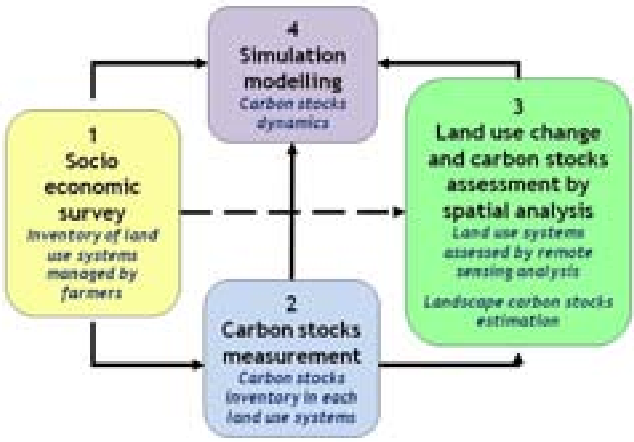


Figure 12. Four main components and outputs under RaCSA approach.

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).

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

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.

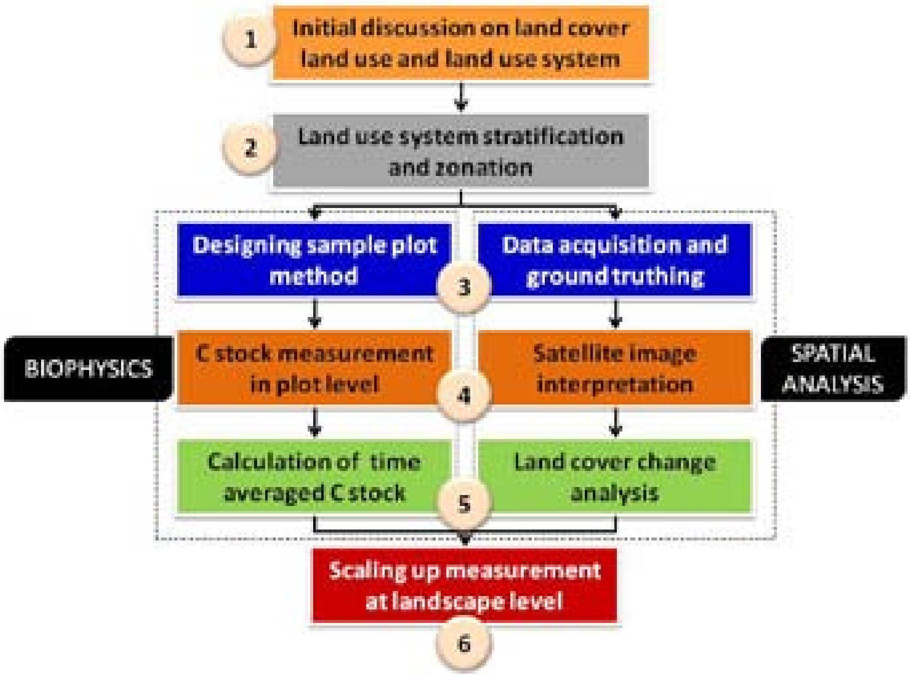


Figure 13. RaCSA in 6 practical steps

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.

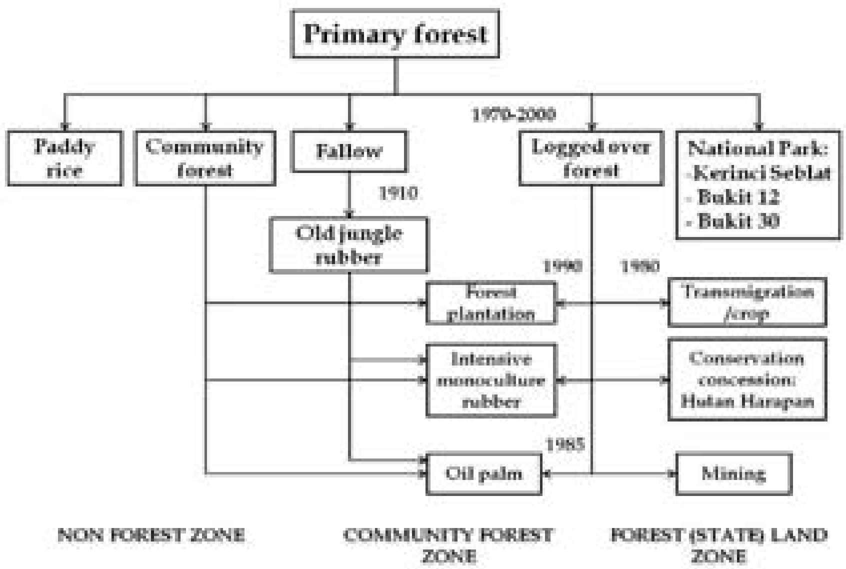


Figure 14. Schematic diagram of LU/LC and LUS dynamics in Jambi, Sumatra, Indonesia, derived from a focus group discussion exercise.

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.

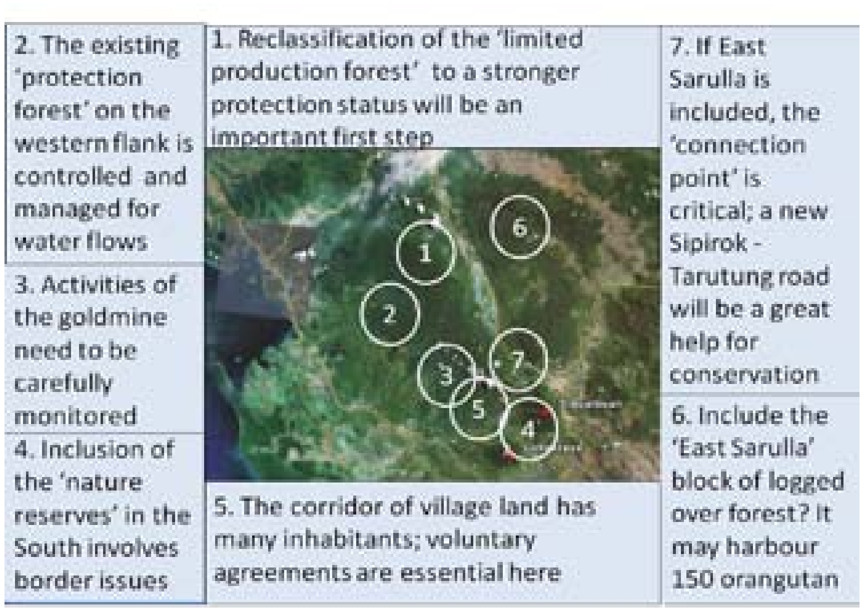


Figure 15. Annotated map of Batang Toru, Sumatra, Indonesia from interviews with key informants (Note: This step is a subset of the DriLUC (Drivers of Land Use Change) tool developed by ICRAF - see http://www.worldagroforestrycentre.org/sea/projects/tulsea/inrmtools/DriLUC).

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-

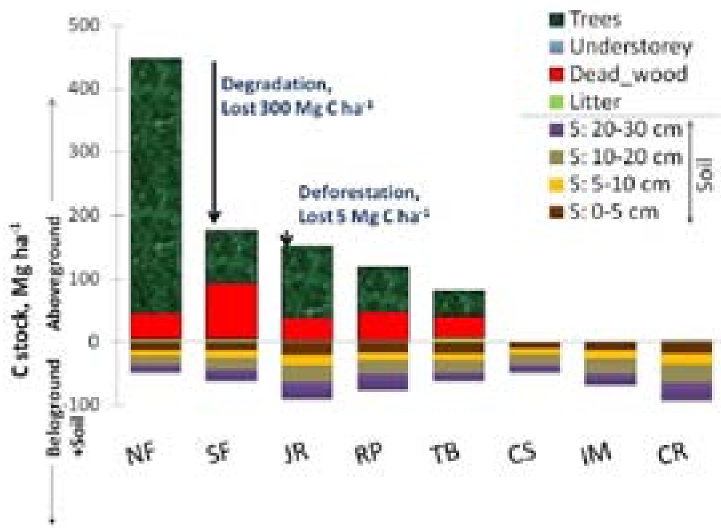


Figure 16. Measurements of five C pools (trees, understory, dead wood, litter and soil) in various land use systems of Jambi; the data still need conversion to time-averaged C stock over the system's life cycle (Tomich et al., 1998).

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

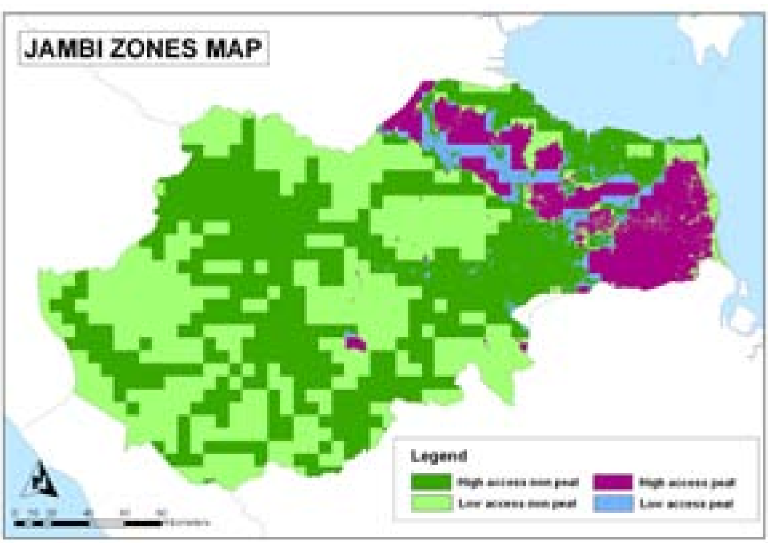


Figure 17. Map of zonation of Jambi, Sumatra based on combination between soil types (peat and non peat) and accessibility (high and low).

- Drivers and trends (Figure 17)

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.

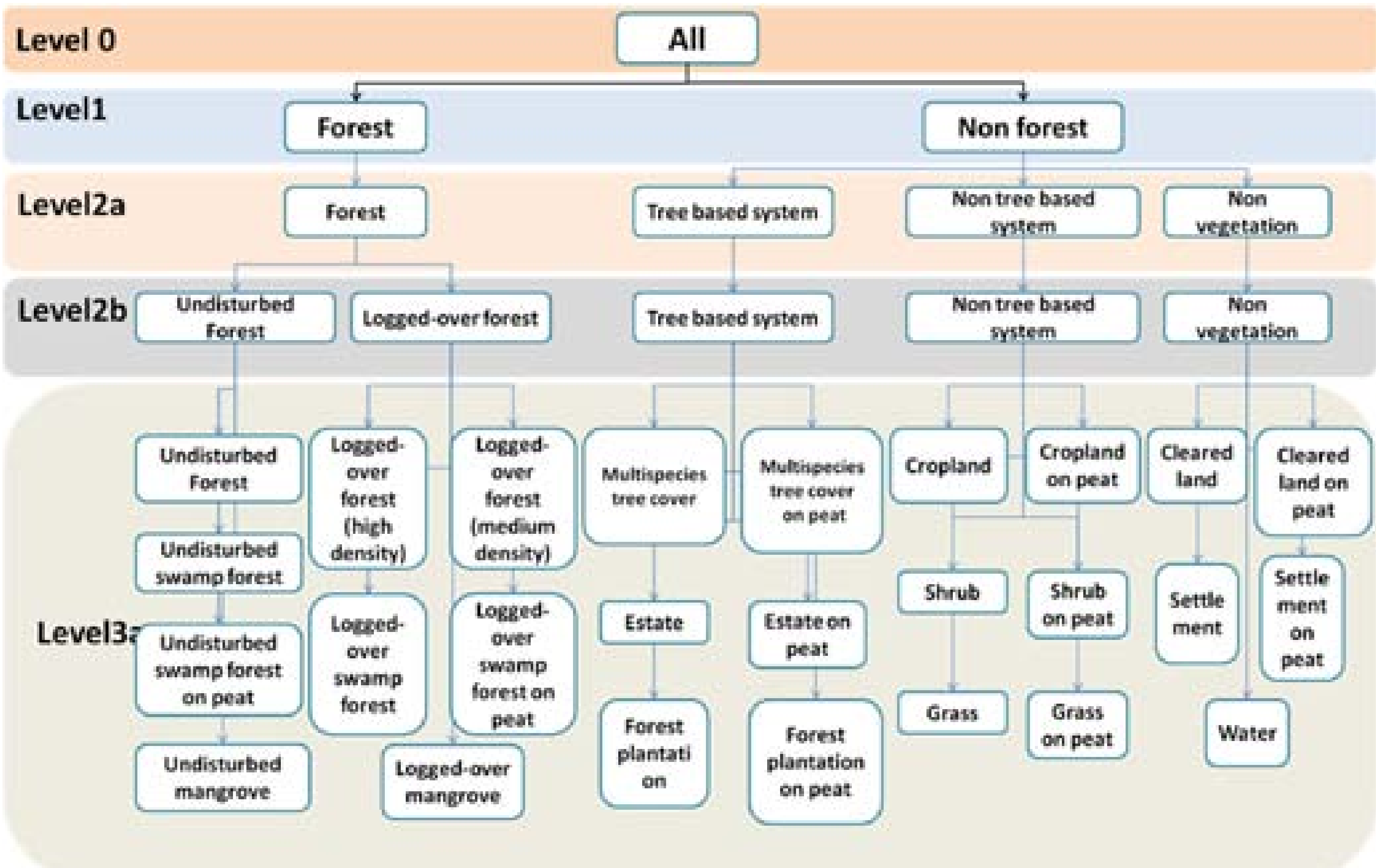
h. Bush/fallow: dominated by non-woody vegetation.

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).

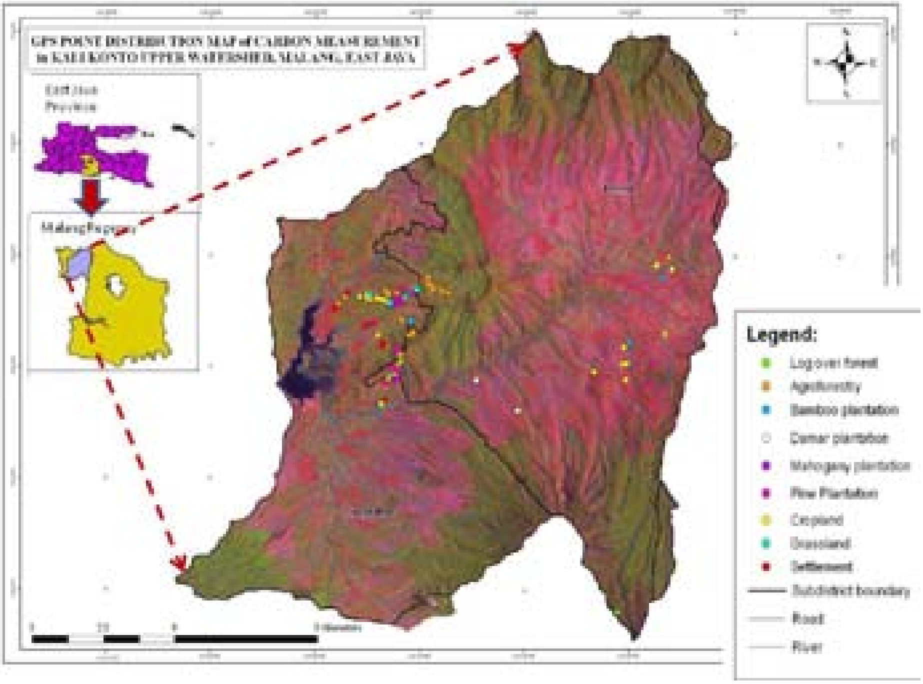


Figure 19. Map showing location of all plots selected for carbon measurements in Kalikonto watershed,

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 m2) 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.

Continued...

Photo 2. Setting up rectangular subplots for measurement in natural forest (A1, A2, A3) and in agroforestry systems (B1,B2,B3), geo-position of each plot should be recorded using GPS.

Procedure

- Set out two 200 m2 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 m2 quadrats (20 m × 25 m) instead of 200 m2.

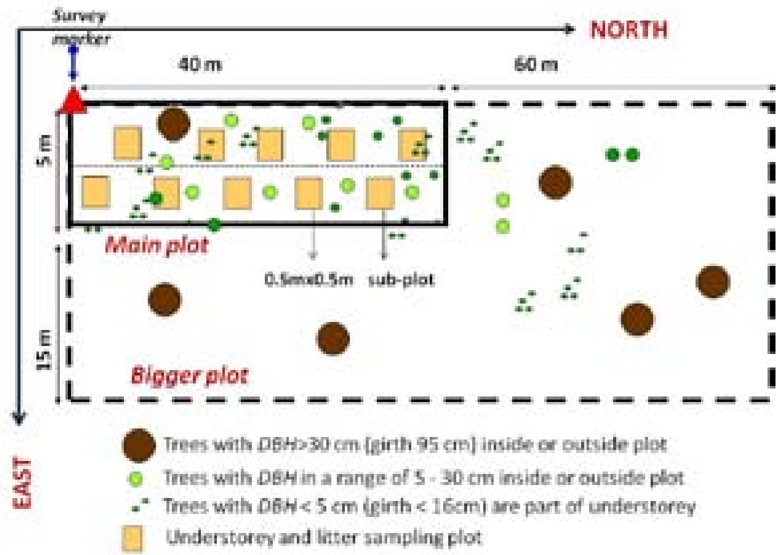


Figure 20. Diagram of nested plot design for sampling in forest and agricultural ecosystem.

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 m2 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.

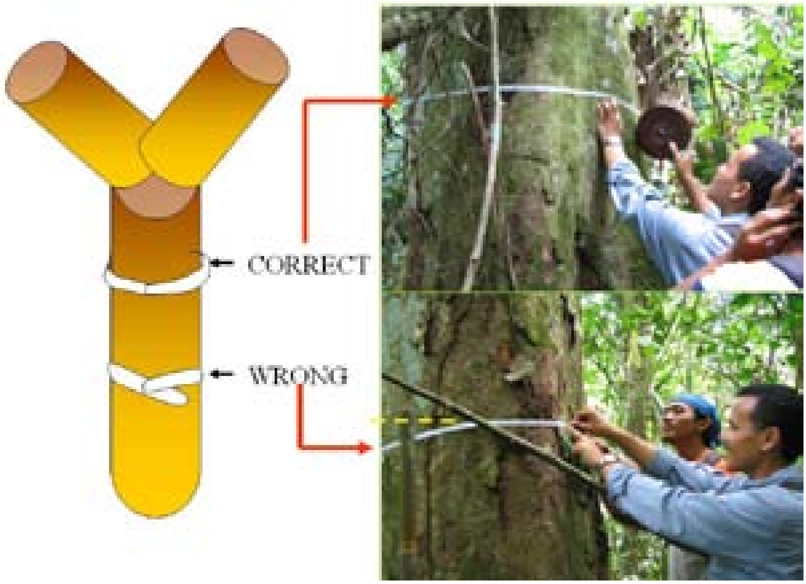


Photo 4. Measuring tree diameter using girth tape. Do not let the tape sag as it must be placed at right angles to the stem of the tree.

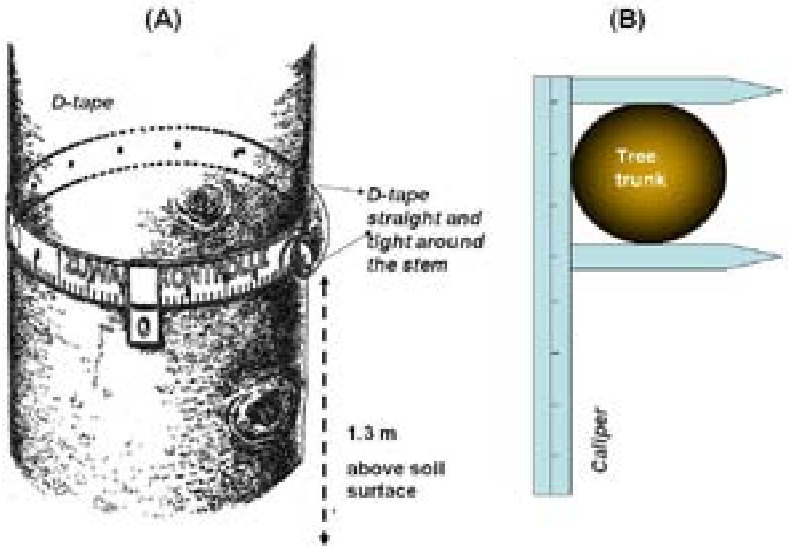


Photo 5. Diagram of measuring smaller tree diameter using d-tape (A) and caliper (B). Keep caliper horizontal around the tree, repeat the measurement from a different angle to reduce bias due to uneven surface on stem (copied from Weyerhaeuser and Tennigkeit, 2000).

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.

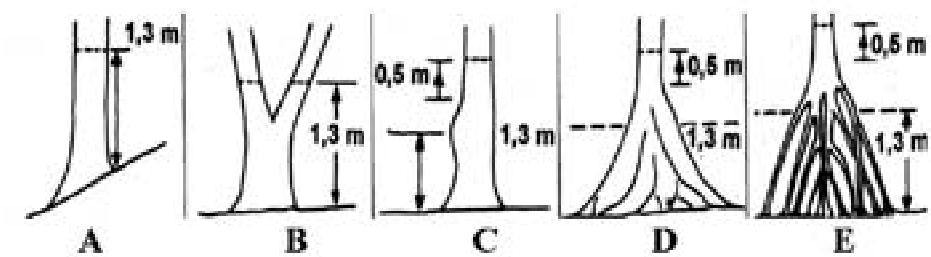


Figure 21. Guide for determining DBH for abnormal trees (Weyerhaeuser and Tennigkeit, 2000).

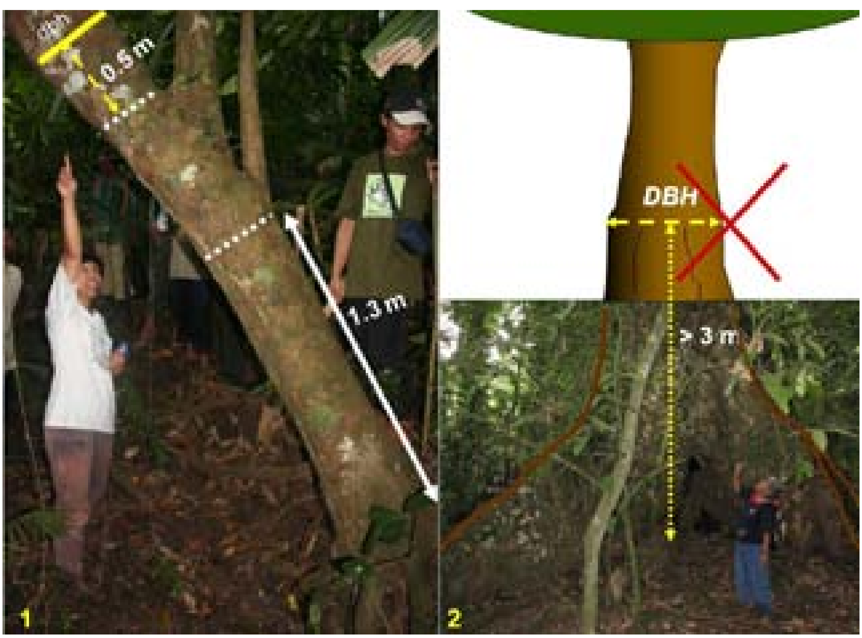


Photo 6. Tree leans and branches after 1.3 m. The measurement should be made at the smoothest part of the main stem, at 0.5 m after the branch. (2) Big trees with plank roots are often found in tropical forests, how to measure tree diameter of this big tree? Do not climb the tree: See Box 8!

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).

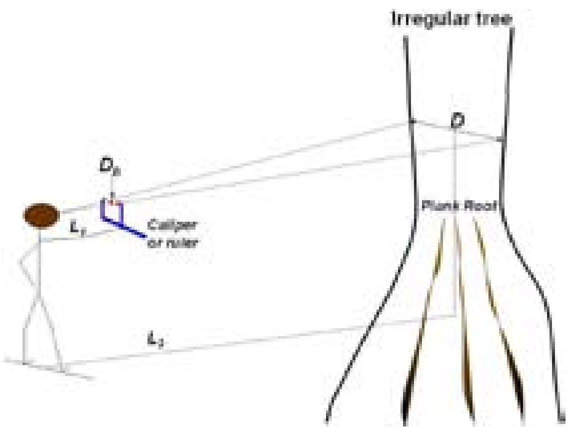


Figure 22. Schematic diagram showing how to measure the diameter of a big tree with plank roots based on a geometric approach.

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. $(AGB)_{est} = 0.0509\ \times \rho D^2H$ 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, g 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, g 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):

$$\mathbf{Y = a\ \rho\ Db}$$

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

Continued...

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

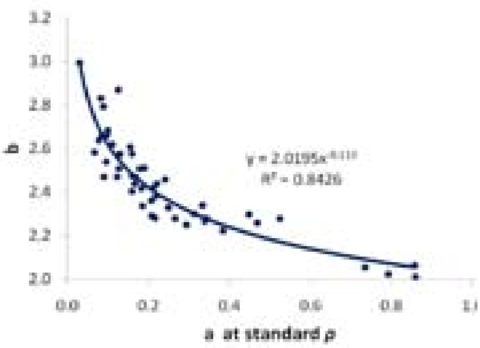


Figure 23. Empirical relationship between a (intercept) and b (power coefficient) of published allometric relations of aboveground tree biomass, after correcting the a parameter for wood specific gravity (ρ).

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.

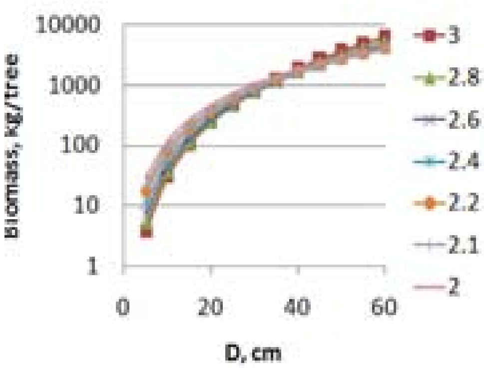


Figure 24. Relationship between stem diameter and tree biomass for allometric relations for different b parameters, in which the a and b parameters are linked as indicated in Figure 23.

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).

2.7.3.1. Understory

Understory (herbaceous) species consist of all plants of the lower canopy levels in a woodland ecosystem, as distinct from emergent, crown or overstory species. Some species commonly found include grasses, ferns and bananas but others may be younger specimens of emergent species. Understory sampling must be carried out destructively.

Equipment needed to sample the understory, litter and soil

1. Measuring tape
2. Quadrat of 1 m × 1 m and 0.5 m × 0.5 m for taking samples of understory and litter
3. Aluminium or wooden quadrat 20 cm × 20 cm × 10 cm and ring sampler (diameter 5 cm) for taking undisturbed soil sample
4. Spade for taking soil sample
5. Small shovel to take soil sample
6. Knife and/or scissors
7. Scales: one allowing weights up to 10 kg (to an accuracy of 10 g) for fresh samples and one with a 0.1 g accuracy for sub-samples
8. Marker pens, plastic and paper bags

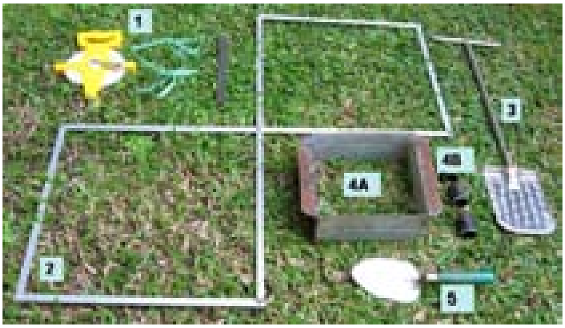


Photo 8. Equipment needed to take samples of understory, litter and soil: (1) Measuring tape, (2) Aluminium quadrat, (3) Spade, (4A) Metal quadrat, (4B) Ring sample, (5) Small shovel

Continued...

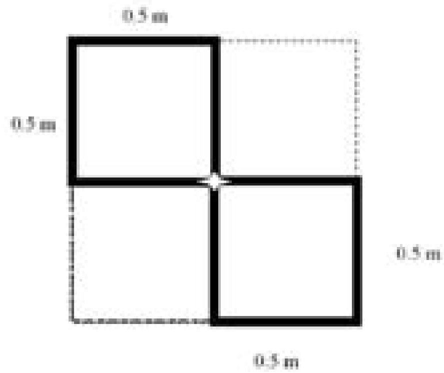


Figure 25. A quadrat is typically a rectangular frame constructed of plastic (pvc), metal or wood that is placed directly on top of the vegetation. Quadrats are also commonly called sampling points. Sampling frames can be used for 1 × 1 m samples, or for two adjacent 0.5 m × 0.5 m samples.

Procedure

- Place sampling frames using metal quadrat of 0.25 m2 (Figure 26, Photo 9) within the 40 m × 5 m transect, as indicated in Figure 20, placing it about 8 m from the start of the transect and then every 6 m along the center line of the transect.
- Cut all vegetation in the quadrat and place it in a plastic bag,
- Weigh directly to get fresh weight (FW) in the field (g/0.25 m2)
- Chop all samples and mix them well before taking subsamples. Weigh about 100 g as a subsample and place it in a paper bag.
- Place subsample in the oven at 85 oC for 48 hours, weigh its dry weight (DW). If oven capacity is limited, samples can be sun dried (on a ventilated plastic shelf system) and only sub-subsamples processed in the oven.
- Record all data into Worksheet 2.

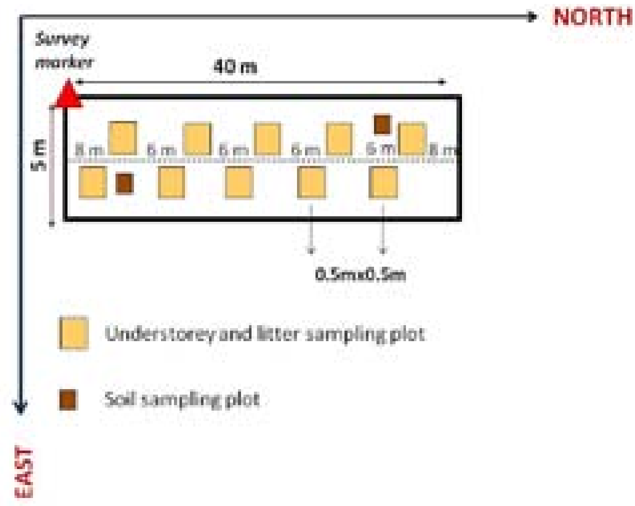


Figure 26. Five sample points (each with two 0.25 m2 samples) for understory, litter and soil sampling within 200 m transect as described in Figure 20.

Photo 9. Understory sampling within a 1 m2 quadrat (1 and 2) and destructive sampling of palm (3 and 4) in agroforestry system.

Box 13. Example calculation of understory biomass

Consider that within a 0.25 m^2 quadrat, the understory sample consists of 500 g of leaves and 500 g stems fresh weight (FW). A subsample of 300 g of each is weighed and then dried in the oven at 80 °C for 48 hours.

Following drying, the subsamples are weighed:

Dry weight (DW) of leaf subsample = 150 g, DW of stem subsample = 200 g, so total DW (leaf and stem) = (150 g/300 g × 500 g) + (200 g/300 g × 500 g) = 583 g per 0.25 m^2.

Total DW understory per m^2 = 583 g × 1 m^2/0.25 m^2= 2332 g =

2.3 kg or 23 Mg ha^{-1}

2.7.3.2. Dead trees as part of necromass

Procedure

- Within the plot of 200 m2 (5 m × 40 m), sample all woody debris and trunks (unburned part), dead standing trees, dead trees on the ground and stumps that have a diameter >5 cm and a length > 0.5 m.
- If dead trees with diameter > 30 cm are present in the sampling plot, whether or not they are included in the transect, a bigger sampling area of 20 m × 100 m is needed, including all dead trees with a diameter > 30 cm.
- Their height (length) is recorded within the 5 m wide transect (see Figure 27 and Photo 10) and the diameter is measured, as well as notes made identifying the type of wood for estimating specific density.
- Record all data into Worksheet 3A for big trees and Worksheet 3B for small trees.

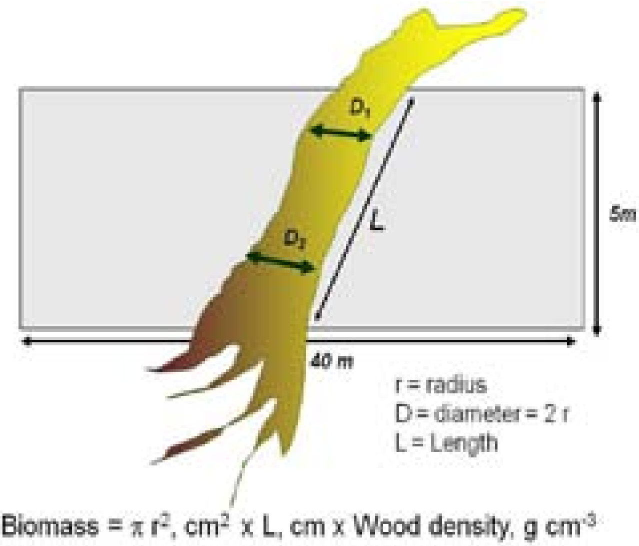


Figure 27. Estimation of weight of felled tree by multiplying wood volume with its wood density.

Photo 10. Measuring length and diameter to estimate biomass of fallen or felled trees in a transect of forest (1) or in agricultural land after slashing and burning (2) and taking sample of litter (leaf, twig, fruit, flowers) on soil surface (3).

2.7.3.3. Litter

Procedure

- Collect a sample of all litter within the same quadrat of 0.50 m × 0.50 m (0.25 m^2) as used for the understory sample; this can be done in two steps.
- Take a coarse litter sample, (any tree necromass < 5 cm diameter and/or < 50 cm length, undecomposed plant materials or crop residues, all unburned leaves and branches). All undecomposed (green or brown) material is collected to a sample handling location for sorting and subsampling.
- Subsequently, collect the fine litter in the organic layer (0–5 cm above mineral soil layer) in the same quadrat (including all woody roots) and dry sieve the roots and partly decomposed, dark litter. If time allows, the sieving can be done onsite, but it may be more convenient to collect bags of the topsoil and process elsewhere.

Sample handling for litter samples

- Coarse litter: To minimize contamination with mineral soil, the samples should be soaked and washed in water; the floating litter is collected, sun dried and weighed; the rest is sieved on a 2 mm mesh sieve and added to the fine litter fraction. Depending on the total amount, a subsample can be taken at this stage to determine the oven-dry correction factor (weigh after drying in an oven at 80 ^{o}C). As an alternative to the washing procedure, samples can be ashed (at 650 ^{o}C) to correct for mineral soil contamination.
- Fine litter and roots (see Photo 11): The litter (including dead roots) and (live) root material collected on the 2 mm sieve (by dry sieving) is washed and dried. The soil passing through this sieve is collected for the 0–5 cm sample for C_{org} or C fraction analysis.
- Record all data into Worksheet 3C.

Photo 11. (1) Fine roots grow in the rich organic layer. (2) Dry sieving to separate fine roots and soil.

2.7.4. Measuring belowground organic pools

The belowground organic pools include the soil C and microbial biomass only, while root C is considered as a part of the plant biomass (see section 2.7.2.4). Soil organic matter does not include forest litter. Soil carbon consists of organic C, inorganic C and charcoal. Inorganic C in the form of carbonate usually exists in calcareous soils, but is insignificant in neutral and acid soils. The main form of soil carbon is soil organic carbon. Soil organic carbon differs greatly between peat soil and mineral soil.

Soil organic carbon consists of a wide range of compounds forming a biochemical continuum from cellular fractions of higher plants through to microbial and humus compounds. Simply, soil organic matter is all organic material (partly decomposed) in the soil which has passed through a 2 mm sieve.

IPCC (2006) separates soil organic matter into: (1) mineral forest soils that typically contain between 20 to over 300 Mg C ha^{-1} depending on the forest type and climatic conditions (Jobbagy and Jackson, 2000); and (2) organic forest soils (peat soil). Carbon content in mineral soils is high in the first 30 cm layer, but peat soils consist mainly of organic matter from the surface to the substratum and therefore its C content is high all the way to the substratum. Every cubic meter of tropical peat contains about 30–70 kg C and this translates to about 300–700 Mg C ha^{-1} per meter of peat depth. With the depth of tropical peat ranging anywhere between 0.5 to more than 10 m, the carbon stock of peat soil may range between 250 to more than 5000 Mg ha^{-1} (Agus and Subiksa, 2008; Hooijer *et al.*, 2010). Vertical and lateral variation of C stock is high for both types of soil and so measuring requires a set and consistent protocol. Soil organic C pools change because of different forest management activities, such as rotation length, choice of tree species, drainage, harvest practices, site preparation (with or without fire) and fertilization.

2.7.4.1. Measuring mineral soil C

Estimation of the C content per unit weight of soil requires the measurement of the concentration of C per soil layer and soil weight, which requires both types of soil sample (Photo 12):

- **Disturbed soil samples** for chemical analysis are samples where the soil has changed dramatically from its original structure in the field. For carbon analysis purposes, the solid soil phase is required from the samples; the soil pore distribution etc. is not necessary. The results will be expressed per unit dry weight of soil.
- **Undisturbed soil samples** for physical property analysis, are required especially for the soil bulk density (specific gravity) of the soil which is essential to convert the soil dry weight into soil volume. For carbon analysis, the important aspect is the oven dry weight of a known volume of sample. Therefore it does not matter if the sample is disturbed for determining the oven dry mass as long as the complete sample of a known volume is used for oven drying. For some other purposes, such as analyzing soil-water relationships, the initial field condition structure should be maintained.

Photo 12. Examples of disturbed (1) taking soil sample using auger, (2) transferring soil sample, (3) sieving to separate any roots and organic materials from soil sample, (4) taking undisturbed soil samples.

A. Sampling disturbed composite soil samples

Equipment for sampling disturbed mineral soil

1. Edelman auger (Figure 28)
2. Machete, hoe or shovel can substitute for the Edelman auger
3. Knife
4. Plastic bags
5. Labeling cards
6. Marker
7. Three 5-liter buckets (may be substituted with 3 large plastic bags)

Figure 28. Edelman soil auger

Procedure for soil sampling

A composite sample is a mixture of samples representing a few sampling points at certain soil depths.

- Choose randomly three to six 0.5 × 0.5 m small plots within the 40 × 5 m transect (Figure 20).
- Remove the organic litter layer, and take the soil samples from the 0–10, 10–20 and 20–30 cm depths using either the Edelman Auger (which is simpler) or a shovel and machete.

Soil sampling using an Edelman auger

- Clean the soil surface of litter and small plants.
- Turn the auger clockwise until its base penetrates the soil to 10 cm depth.
- Pull the auger out gently by slightly turning it counter clockwise.
- Transfer the sample to the first bucket, marked “0–10 cm”. Break up the large clods of soil by hand.
- Continue sampling the 10–20 cm layer and then the 20–30 cm layer with the same procedure, transferring the samples to the buckets marked “10–20 cm” and “20–30 cm”, respectively.

- Move to the next sampling point (small 0.5 × 0.5 m plot) and take soil samples by layers as explained previously.
- Transfer each sample from the same depth into the respective buckets until all of the predetermined number of samples within the 40 × 5 m transect have been collected.
- Mix the samples in each bucket thoroughly.
- For each bucket, transfer about 0.5 kg of soil to a plastic bag for chemical analysis and another 0.5 kg into a separate plastic bag for archiving; the remainder can be discarded.

Soil sampling using a shovel and machete

- Dig a pit 40 × 40 × 40 cm using a shovel, or a combination of a hoe and machete.

- ◦ Slice about a 3 cm-thick vertical section of soil from one side of the pit wall using a machete from the 0–10 cm depth. Make sure to take an equal representation of the segment soil depth.
- ◦ Transfer the soil to the first bucket.
- ◦ Take a similar slice from the 10–20 cm depth and transfer it to the second bucket and then take a slice from the 20–30 cm depth and transfer it to the third bucket.
- ◦ From the other sample plots, take the respective samples from each depth and combine them with the samples from other plots taken at the same depth in the correct bucket.
- ◦ For each bucket, transfer about 0.5 kg of soil to a plastic bag for chemical analysis and another 0.5 kg into a separate plastic bag for archiving; the remainder can be discarded

Processing samples

- Air-dry the soil samples for a few days by placing them in separate trays in a room that is well ventilated and free of dust and draughts. Break up any clay clods, and crush the soil lumps so that gravel, roots and large organic residues are removed.
- Transfer the samples into plastic bags or clean paper boxes. Using a waterproof marker pen, label each container clearly with the sampling date, sample depth, location and GPS coordinates. Place each plastic bag into a second plastic bag to prevent any breakage and sample loss during transportation.
- Send the soil samples to a certified laboratory for carbon content analysis using the method of Walkley and Black (1934). Depending on the need, other chemical analyses could also be requested using the same samples.
- The laboratory analysis will present the soil carbon content in terms of percentage by weight or in terms of g kg^{-1}, where 1% by weight = 10 g kg^{-1} = 0.01 kg kg^{-1} = 0.01 Mg Mg^{-1}.

Example of Calculation

How much C stock (Mg ha^{-1}) is in the soil layer sampled at 10 cm depth, if the soil bulk density is 1.0 kg dm^{-3} or 1.0 Mg m^{-3} and the concentration of C^{org} in the soil is 2.0%?

Soil weight per ha = 100 × 100 × 0.10 × 1.0 Mg m^{-3} = 1000 Mg or 1000 t

Soil C stock = 1000 t × 0.02 = 20 Mg ha^{-1} or 20 t ha^{-1}

B. Taking undisturbed soil samples and determining soil bulk density

There are various methods for sampling soil bulk density: (1) using a sample ring (tube) or a metal frame that can carry out the same function as the ring, (2) the excavation method and (3) the clod method. The sample ring technique is the most simple and most commonly used and is explained below. Readers who are interested in the other two methods are referred to Blake and Hartge (1986) or its adaptation in the Indonesian language (Agus ., 2007).

B.1. Taking undisturbed soil sample using a metal ring

Equipment for sampling undisturbed mineral soil

1. Sample ring (7.63 cm diameter and 4 cm tall or adjusted according to other available laboratory apparatus) made of copper or stainless steel tubing (Photo 13). The size of the ring may vary, but to minimize sample compaction, the ideal ring dimension should meet the criteria:

$$\frac{D_o^2 - D_i^2}{D_i^2} \le 0.1$$

Where, Di is the inner diameter and Do is the outer diameter. A ring size commonly used is 4 cm long, with 7.63 cm inner diameter and 7.93 cm outer diameter.

2. Machete, hoe or shovel
3. Knife
4. Cutter or scissors

Continued...

5. Plastic bags
6. Labeling cards
7. Marker pen
8. Rubber mallet

Photo 13. Sample ring (sample tube) with upper and lower lid (left). The bottom edge of the ring is sharpened (right) to minimize soil compaction.

Procedure (modified from Suganda *et al*., 2007)

- Clean soil surface of litter and small plants. Using a machete, dig the soil around the place where the ring sample will be taken (Photo 14).
- Place the sample ring on the soil surface and push it into the ground. If the soil is hard, use a wooden block on top of the ring and then push or hammer the block gently using a rubber mallet or a hammer until about three quarters of the ring penetrates the ground.
- Place another ring on top of the first one and push until it penetrates 2 cm into the ground.

  Note: With this method the sample depth will be 2–6 cm. For sampling to deeper depths, for example at a depth of 12–17 cm, dig a small pit of 30 × 30 × 10 cm depth and place the first ring on the bottom of the pit. Then, use the same procedure as for the first layer.

- Separate the second ring from the first one.
- Dig out the first ring using a shovel or a machete.

  Note: Avoid soil compression (as shown by the lower soil surface inside relative to that outside of the ring). If this happens, use a larger, thinner and sharper ring. Avoid taking the sample when the soil is too dry as it may easily crumble.

- Cut excess soil carefully from the top of the ring until the soil is level with the top of the ring and then put a lid on the top of the ring. Do the same for the bottom of the ring.
- Label the lid on the ring top showing depth information, the date of sampling and the location (including GPS position) of the soil sampling (Photo 14).
- Arrange the samples in the rings in a wooden casing or a cardboard box with a maximum of 4 layers of rings. Use a layer of foam to minimize vibration.
- Send the samples in the box to a certified soil physics laboratory.

Photo 14. Steps of soil sampling using a sample ring (from upper left corner to the lower right corner).

Determining soil bulk density

- Remove the lid of the ring and place the sample from the ring into an aluminum can.
- Dry the soil in an oven at 105°C for 48 hours. Then, place the samples in a dessicator for about 10 minutes.
- Weigh the sample dry weight (M_s) + ring weight (M_r) + weight of the can (M_c).

- Wash and dry the ring and the can in an oven at 105°C for 2–3 hours. Weigh the ring (M_r) and the can (M_c).
- Measure the ring inner radius *r* and height *t* and calculate the inner volume V_t, which is the volume of the bulk soil sample using the equation below.

$$V_t = \pi r^2 t$$

- Calculate the soil bulk density D_b using the equation below.

$$D_b = \frac{M_s}{V_t} = \frac{(M_s + M_r + M_c) - (M_r + M_c)}{V_t}$$

Note: the unit of D_b may be in g cm^{-3} or Mg m^{-3}, where 1 Mg = 1 mega gram = 1 tonne = 1000 kg.

- Record all data into Worksheet 4.

B.2. Sampling undisturbed soil using a metal frame

The procedure using a metal frame is basically the same as for taking samples using the sample ring. However, because of the large dimension of the metal frame, the procedure will require weighing the sample in the field, sub-sampling and then determining the water content in the laboratory. The large sample size (2000 cm^3 depending on the dimension of the frame), provides a good sample for estimating the soil wet weight but subsamples will need to be taken because it is not possible to oven-dry such a large sample volume. The subsampling involves error and thus this method may be less convenient and no more accurate than using the sample ring.

Equipment for sampling undisturbed mineral soil

1. Use an open-top and open-bottom steel box or frame with dimensions of 20 × 20 × 5 cm3 = 2000 cm^3 or any other convenient dimensions. The bottom edge should be sharpened for easy penetration into the soil (see Photo 15)
2. Wooden hammer or rubber mallet
3. Spade or shovel
4. Knife or sharp machete for removing excess soil adhering to the frame
5. Plastic bags, rubber bands and marker pen
6. Scales with 5 kg capacity

Photo 15. Equipment for sampling undisturbed soil: (1) spade, (2) a piece of wood, (3) rubber mallet, (4) steel box, (5) wall scrapper, (6) hand shovel, (7) knife

***Procedure*:**

1. Take soil samples close to the sampling points used for understory sampling (see Figure 27) but avoid areas compacted as a result of other sampling activities.
2. Remove the litter layer, push the frame down gently into the soil surface (0–5 cm depth layer); if the sample cannot be inserted smoothly (for example, due to woody roots or stones), try again at a point nearby.
3. Remove all soil around the frame and cut the soil beneath the frame using the shovel.
4. Remove excess soil from above the frame using a knife, then, cover the top of the frame using a piece of lumber layered with a plastic sheet. Cut a smooth surface on the bottom of the frame.
5. Remove all soil from the frame to a plastic bag and weigh the soil for the wet weight ($M_s + M_w$) of the 2000 cm^3 of soil.
6. Take about a 100 g subsample and transfer it to a plastic bag; tie the bag to minimize evaporation. Label the sample properly with the date of sampling, location (including GPS position), sampling depth and the name of the project and the surveyor.
7. Repeat the above sampling procedure for the 10–20 and 20–30 cm depth layers, taking samples at around depths of 15 and 25 cm.
8. Determine the wet weight of each subsample using an aluminum can ($M_s' + M_w' + M_c$), dry each sample in an oven at 105^{o}C for 24 hours and determine the oven dry weight, ($M_s' + M_c$).
9. If three points are sampled at three depths, there will be nine samples of the 2000 cm^3 volume and nine subsamples for water content determination.

Photo 16. Taking undisturbed soil sample for measuring bulk density using metal frame: (1) inserting the steel box into soil, (2) taking out the undisturbed soil sample using a shovel, (3) removing excess soil from above the frame using a knife, (4 and 5) transferring soil sample into a plastic bag and ready for weighing

Calculation

Volume of soil (V) = 2000 cm^3

Gravimetric water content, w, from the subsample:

$$w = \frac{M_w}{M_s} = \frac{(M_s' + M_w' + M_c) - (M_s' + M_c)}{M_s'}$$

Soil bulk density

$$D_b = \frac{M_s}{V_t} = \frac{(1-w) \text{x} (M_s + M_w)}{V_t}$$

Example 1.

Suppose the fresh soil weight of the 2000 cm^3 soil (M_s + M_w) is 2400 g. The fresh soil weight of the subsample (M_s' + M_w') is 130 g and its dry weight (M_s') is 100 g. Calculate the soil bulk density using the following equation.

w = (130 g – 100 g) / 100 g = 0.3 g g^{-1} = 30% by weight

D_b = {(1-0.3) g g^{-1} × (2400 g)}/2000 cm^{-3}

= 0.84 g cm^{-3} = 0.84 Mg m^{-3}

Example 2.

How much C stock (Mg ha^{-1}) is in each of the 0–10, 10–20 and 20–30 cm soil layers if the soil bulk density of the three respective layers is 0.9, 1.1 and 1.2 g cm^{-3} and the soil organic carbon content (C_{org}) is 3, 2 and 2%, respectively, by weight?

Answer:

Soil dry weight per ha for:

0–10 cm depth = 100 x 100 × 0.10 m × 0.9 Mg m^{-3} = 900 Mg

10–20 cm depth = 100 × 100 × 0.10 m × 1.1 Mg m^{-3} = 1100 Mg

20–30 cm depth = 100 × 100 × 0.10 m × 1.2 Mg m^{-3} = 1200 Mg

Soil C_{org} by weight for

0–10 cm depth = 3% by weight = 30 g kg^{-1} = 0.03 Mg Mg^{-1}

10–20 cm depth = 2% by weight = 20 g kg-^{1} = 0.02 Mg Mg^{-1}

20–30 cm depth = 2% by weight = 20 g kg^{-1} = 0.02 Mg Mg^{-1}

Soil C_{org} for each 10 cm depth increment for 1 ha area = soil dry weight for each 10 cm depth increment for 1 ha area × C_{org} by weight.

0–10 cm depth = 900 Mg × 0.03 Mg Mg^{-1} = 27 Mg

10–20 cm depth = 1,100 Mg × 0.02 Mg Mg^{-1} = 22 Mg

20–30 cm depth = 1,200 Mg × 0.02 Mg Mg^{-1} = 24 Mg

Thus C_{org} for the total 0–30 cm layer for the 1 ha area = (27 + 22 +24) Mg = 73 Mg

Remember: Quality data on this parameter are scarce and the potential land use impacts are large

2.7.5. Estimating plot level C stock

After the C stock for each component has been determined (see Worksheets 1A, 1B, 2, 3A, 3B, 3C, 4) within the plot, copy the results into a new worksheet to determine the total C stock of the whole plot (Table 5).

Table 5. Calculation for total C stock of each plot.

LUS	Rep	Tree*) Mg ha^{-1}	Under-story Mg ha^{-1}	Litter Mg ha^{-1}	Root **) Mg ha^{-1}	Soil 0-5 cm Mg ha^{-1}	Soil 5-15 cm Mg ha^{-1}	Total C stock Mg ha^{-1}
		1	2	3	4	5	6	1+2+3+4+5+6
	1							
	2							
	3							
	4							
	5							
	6							
	.....							
	.....							
	100							

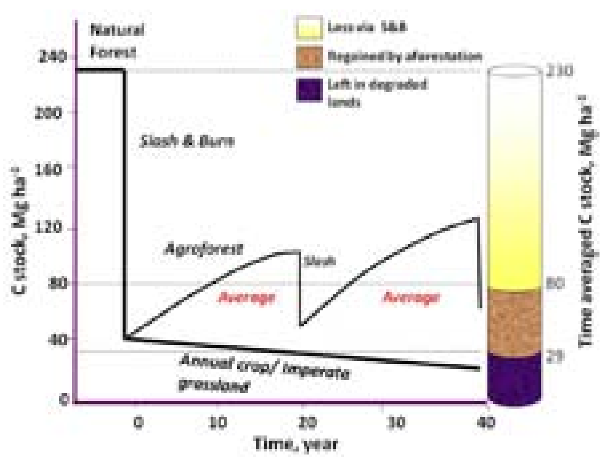


Figure 29. Course of system C stocks (biomass and soil, solid line) and time-averaged C stocks (dotted lines) in an agroforestry system versus crop followed by grasslands at the margins of humid tropical forest (IPCC/LULUCF-section 4, 2000). S&B = slash and burn.

2.7.6. Calculating time-averaged C stock of a land use system

Determining the typical C stock value starts by recognizing the life cycle of the system. For land use systems that are in equilibrium (for example, natural forest) with regard to their age (all ages are equally likely), the time-averaged value will also be the spatially-averaged value, when applied to a sufficiently large landscape. Such a typical value must represent the spatial average of the preceding land use, as well as typify the temporal average of the new system over its life cycle. It must equal the sum of gains and losses (harvesting) that will be detailed in the accounting system selected. For systems that are increasing in area or are in decline, the spatial average will be lower or higher than the time-averaged value, respectively. Therefore, the C loss or sequestration potential of a land use system is NOT determined by the maximum C stock of the system at any one point of time, but rather by the average C stored in that land use system during its rotation time (ASB, 1996). This typical-C stock value is also called the **time averaged C stock** (IPCC, 2000).

In agroforestry systems, as farmers incorporate various trees species on their farms, this will affect C stocks differently to cropland or forest management. For example, trees in an agroforestry system are harvested more frequently than under forest management. For one reason or another, farmers may also plant more new trees on their land that are the same species as before or they may be different species. Therefore to extrapolate the C stock of an agricultural plot to the landscape level requires the averaged C stock (Palm *et al*., 2005) as shown in Figure 29. The time-averaged C stock takes into account the dynamics of the system (at the landscape level) that include tree regrowth and harvesting and allows for a comparison of land use systems that have different tree growth and harvesting rotation times and patterns.

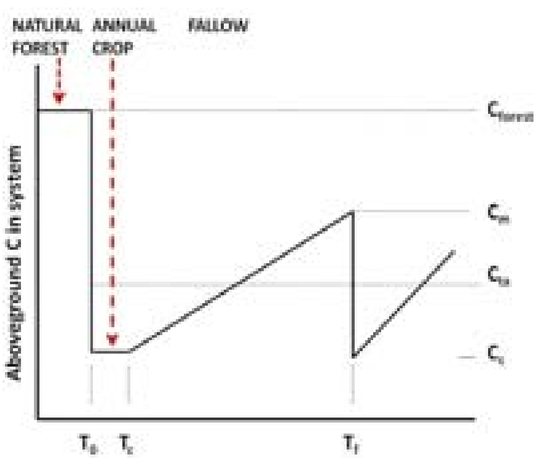
Four factors affect the time-averaged C stock: (a) the C accumulation rates, (b) the maximum and minimum C stored in the system during a full rotation, typically just before and just after a harvest event, (c) the time it takes to reach maximum carbon and (d) the rotation length of the system.

2.7.6.1. Calculating time-averaged C stock

For this calculation, the time-averaged C stock is calculated under two scenarios: (a) after forest clearing and the establishment of a crop fallow system (see Figure 30); and (b) after forest clearing and the establishment of an agroforestry system or tree plantation system (see Figure 31).

a. Time-averaged C stock after forest clearing and establishment of crop fallow system

Carbon accumulation rates (I_c) in Mg C ha^{-1} yr^{-1} for the aboveground vegetation regrowth are calculated as the C stock value of the sampled vegetation (C_s) divided by the age (T_s) of vegetation. It is assumed that the C increase rates (I_c) are linear throughout the time period of vegetation regrowth after clearing (T_f), at least for the first 20 years. The maximum C stored in fallow (C_m) at the time of clearing (T_f) is calculated as $C_m = I_c \times T_f$. If the time averaged-C stock for a crop-fallow system is too small it can be neglected; the C stored in a short cropping phase is essentially the C stored in the fallow vegetation at the time of re-clearing (C_m) divided by 2, or it can be calculated as the C accumulation rate (I_c) times the fallow period (T_f).



Where,

C_{ta} = Time averaged C stock

C_m = C in fallow at time of clearing

C_c = C in crop, assumed to be negligible

T_f = Time (years) in fallow phase

T_c = Time in crop phase, assumed short compared with Tf

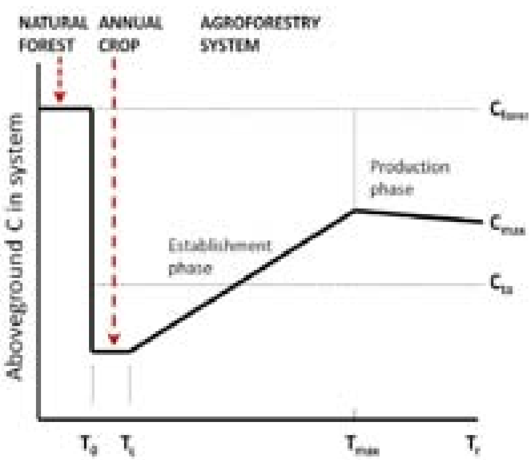
C accumulation rate = $I_c = (C_m - C_c) / (T_f - T_c)$,
or if T_c and C_c are small, then $I_c = C_m / T_f$

Time-averaged C stock = $(I_c \times T_f) / 2$,
assuming T_c and C_c are small

Figure 30. Schematic of the changes in C stocks and means for calculating time-averaged C stock after forest clearing and establishment of a crop-fallow system (Palm et al., 2005).

b. Timeaveraged C stock after forest clearing and establishment of agroforestry system

The maximum C stock (C_{max}) of an agroforestry system may be reached at a time (T_{max}) just before the end of rotation (T_r) as shown in Figure 31. For example, a coffee plantation may reach the maximum C stock in 7 years (establishment phase), but production continues for an additional 5 years (production phase), giving a rotation time (T_r) of 12 years, at which time the plantation is cut and re-established. The timeaveraged C stock for such a land use system is determined as the weighted average of the timeaveraged C stocks for the different phases of the rotation.



Where,

C_{ta} = Time-averaged C stock

C_m = C maximum in agroforestry system at time before end of rotation

T_r = Time of rotation

T_{max} = Time at C stock reaching maximum

Maximum C in system = $C_{max} = I_c \times T_{max}$

Time averagedC stock in system = $LUCS_{ta}$ = weighted mean (C_{ta} establishment and production phases)

C_{ta} establishment phase = $C_{estab} = (I_c \times T_{max}) / 2$

C_{ta} production phase = $C_{prod} = C_{max} = [(C_{estab} \times T_{max}) + (C_{prod} \times [T_r - T_{max}])] / T_r$

Figure 31. Schematic of the changes in C stocks and means for calculating time-averaged C stock after forest clearing and establishment of agroforestry or tree plantation systems (Palm et al., 2005).

Example of calculation

A coffee plantation has an establishment phase of 7 years to reach maximum biomass, followed by 5 years of production before cutting and re-establishment, giving a rotation length (T_r) of 12 years. The values of I_c = 2.2 Mg C ha^{-1} yr^{-1}, T_f = 7 years and C_{min} = 0 are consistent with a C_{max} value of 15.4 Mg ha_{-1}. How much time-averaged C stock is there in the coffee plantation?

To determine the time-averaged C stock of a land use system, it is necessary to know the C stock at any point in time.

Timeaveraged C stock (C_{ta}) for the establishment phase

(C_{estab}) = $(I_c \times T_f)/2$ = (2.2 Mg C ha^{-1} yr^{-1} × 7 year) / 2

= 7.7 Mg C ha^{-1}

The time-averaged C stock (C_{ta}) for the entire system rotation is the weighted average for the three phases that is, the crop phase, fallow phase and production phase. The C stock at crop phase is neglected.

C_{ta} whole system = $[(C_{estab} \times T_{max}) + (C_{prod} \times [T_r - T_{max}])] / T_r$

= [(7.7 Mg ha^{-1} × 7 years) + (15.4 Mg ha^{-1} x [12 years - 7 years])] / 12 years

= (53.9 Mg ha^{-1} + 77 Mg ha^{-1})/12

= 10.9 Mg ha^{-1}

Box 14. Measuring C stock for calculating time-averaged C stocks

For monoculture or plantation system (single rotational system)

- Select plots of different ages of trees in the selected area, if possible use a minimum of 4 different ages.
- Measure diameter of all trees in each plot according to protocol/ methods in section 2.7.1. (Calculate tree biomass using the correct allometric equation.

Continued...

- At the plot level, measure the necromass and soil organic matter as explained in section 2.7.3.
- Calculate the total C stock per hectare by summing C stock of biomass, necromass and soil organic matter [Mg ha^{-1}].
- Develop the total C stock equation for the monoculture per life cycle. Find the value of the median C stock.

Example:

- In a landscape there are four age groups of mahogany plantation aged 5, 15, 25 and 30 years.
- Each sampling plot of 200 m2 consists of 20 trees. Measure all the C components of each plot (biomass, necromass and soil organic matter) according to the procedures in section 2.7.2 ., section 2.7.3 and section 2.7.1.
- Calculate the total C of the different ages of tree (biomass, necromass and soil organic matter).
- Based on the C data obtained from the four different ages of trees, a C regression curve can be developed Y=13.464 e0.0733x, where Y = C stock (Mg ha^{-1}) and X = time (year) (see Figure 32).

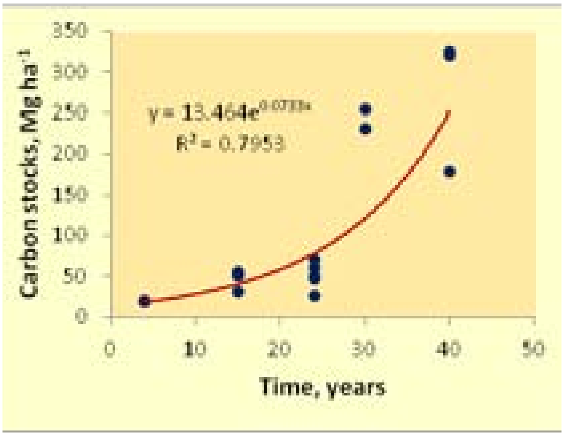


Figure 32. Increment of carbon stock (Mg ha^{-1}) in mahogany monoculture system in Malang, East Java.

Continued...

Usually mahogany is harvested when it is about 40 years old, so the median age is 20 years and this can be integrated from the above equation in Figure 32 ($Y=13.464\ e^{0.0733x}$). In this rotation, the time-averaged C stock is 290 Mg C ha^{-1} and this value should be used for scaling up the C stock to the landscape level.

Photo 17. Agroforestry consists of various tree species. (1) A simple agroforestry system of pine intercropped with coffee, (2) a mix of cinnamon with fruit trees (like durian, avocado, jackfruit) and cardamom as an understorey, (3) more complex agroforestry system with a coffee-based system using fruit and timber trees as shade trees, (4) mixed fruit trees such as durian, mangosteen, jackfruit and understorey ground cover of taro, pandan (Pandanus amarylifolius) and sometimes also lemongrass (Cymbopogon).

For mixed systems or agroforestry system

- Within a landscape, select plots in various types of agroforestry system, for example, agroforestry coffee, agroforestry cacao, mix fruit trees, mix timber trees (see example in Photo 17), since their biomass values will differ between plots. If possible, select different stages of each agroforestry system: young, medium and old.
- Measure all biomass of trees and understorey, necromass and litter, as well as soil organic matter as described earlier in section 2.7.1.

Continued...

Estimate total C stock of each plot by summing the C stock of all components.

- Calculate the average total C stock of the different types of agroforestry systems.

Example

Measurement of C stock in various agroforestry coffee-based systems in Jember (ICCRI, 2008). The coffee plots were derived from natural forest at times ranging from 2 up to 35 years. Leucaena leucocephala was planted as shelter for the coffee trees and to fix free N to improve soil fertility. The rotation time for coffee agroforestry is usually about 30–35 years, so the median time was about 15 years.

Carbon stock in agroforestry coffee system is increasing with time (Figure 33): $Y = 11.921e^{0.0975X}$, where Y = C stock (Mg ha^{-1}), X = time (years) since the forest was converted to a coffee garden. The value of C increment is about 2.8 Mg ha^{-1}, producing a time-averaged C stock value of 15 × 2.8 Mg ha^{-1} = 42.7 Mg ha^{-1}.

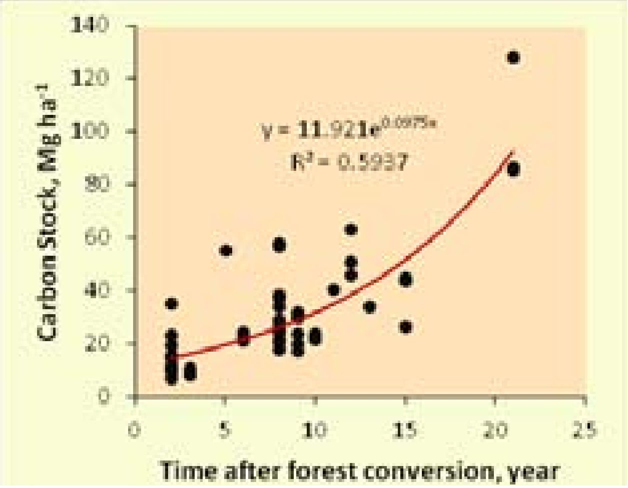


Figure 33. Increment of carbon stock (Mg ha^{-1}) in (simple) coffee-based agroforestry system in Malang, East Java

2.8. Step 5: Groundtruthing, satellite image interpretation and change analysis

The fifth step of RaCSA aims to collect geo-referenced information about LUS from field observations and produce a time series of land use/land cover maps. Land cover is usually considered to be a snapshot of the vegetation cover of an area at one particular time. In such a case, amidst the technical complexities of the satellite image interpretation, it is quite straightforward to determine the land cover in one particular area at time x. However, as soon as land management types are encountered that include cycles and stages of different land cover types, a different level of complication arises. The vegetation cover seen at time x cannot tell the whole story of the dynamics of the C stock in one rotation period and therefore the snapshot has to be treated as a part of the whole cycle. This is referred to as land use systems (LUS) as discussed above. Agroforestry systems and plantations are good examples of land use systems. In most cases, if defined properly, land use systems more precisely describe the dynamics of the C stock rather than land cover types do. Often, but not always, management types can also be treated simultaneously in land use systems, rather than by creating another layer of zonation as we discussed above. The choice should take into consideration the specific landscape contexts, the parsimony of the schemes and the optimization of errors. When plots are measured in the field, the label attached to the plot is LUS rather than land cover, which is a product of the satellite image interpretation. Therefore the lookup table, produced from Step 2, which links land cover types to land use systems needs to be consulted from time to time.

To be able to correctly assess the spatial configuration of land use system in a landscape, up-to-date methods for image acquisition and processing should be used. This is a rapidly changing area of development. In general, three components of image processing are required: groundtruthing, satellite image interpretation and change analysis. In this context, there is an ever-increasing choice of satellite images and techniques for (automatic, supervised or manual) image interpretation after pre-processing of the image.

2.8.1. Groundtruthing

Groundtruthing or the relationship between plot level observations, the stratum allocation (type of land cover) and quantitative properties is usually separated into a training (calibration) and a validation (accuracy measurement) phase, with separate datasets for the two steps. Sufficient numbers of geo-referenced samples are collected through field observations using a global positioning system (GPS).

Objectives:

- To match particular spectral signatures from remote sensing with particular land cover types on the ground.
- To increase the accuracy of image interpretation.

Factors to consider:

- Size of area of interest. Large area of interest will require more groundtruthed samples.
- Variations in terms of factors that can affect spectral signature in the area such as topography.
- Spatial distribution of samples for each land use system. Ideally, groundtruthed samples have to be well distributed over the area of interest.
- Variations of vegetation structure between/within land cover.
- Location of cloud cover on the satellite image. Groundtruthed samples should avoid locations that are covered by cloud in the satellite image.
- Level of familiarity of the technical interpreters with the on-the-ground reality of the particular landscapes.
- Techniques of satellite image interpretation.

Pre-requisite data:

- List of land cover types, land use systems, abiotic and management strata/

zones (classification and stratification/zonation schemes).

- Satellite images to be processed.
- Appropriate geographic projection and coordinate system for the area of interest.
- Accessibility maps (roads and rivers).

Activities:

- Decide on how many weeks the groundtruthing will take after consulting the budget.
- Prioritize areas of a peculiar nature: those that cannot be visually recognized immediately, rough topography, and rapid changes may all stand out in terms of their spectral signatures.
- Stratify areas based on variations in topography and spectral signatures (presumed land cover types); determine how many GPS points should be collected in each one.
- Using the pre-requisite data, delineate strata.
- Decide the most efficient route to be taken using accessibility maps.
- Field observations.
- Field data inventory and post processing.

Output:

- Delineated maps, number of GPS points to be collected in each location, for each strata/zone and land cover type.
- Two sets of GPS points: training set and validation set.

2.8.2. Satellite image analysis

The main objective of satellite image analysis is to produce time series of land use/land cover maps to be linked up with carbon stock measurement through a lookup table from Step 2. Several issues need to be understood regarding time series analysis using satellite images:

- Time series generally have to deal with multiple types of imagery, detail and accuracy of interpretation; for the pre-satellite period, various land cover maps provide indications, but have been derived using different standards.
- With the degradation of the image quality of Landsat imagery as a result of technical problems, recent images from other sources may need to be used, but this may result in differences in interpretation, especially at the margins of strata or land cover classes.
- Where composite images are used from multiple observation dates, it is not uncommon to see differences in interpretation of a continuous landscape at the edges of images that were merged.
- Cloud cover and its shade is a problem, especially in the humid tropics where cloud-free images are scarce. The usual assumption that such clouds are randomly distributed spatially and do not affect the estimate of mean properties is incorrect in terrain where clouds are more likely to be surrounding mountains and peaks. Differences of land cover with elevation have to be taken into account.

Objective:

To label spectral signatures of land cover types with high accuracy in the time series of satellite images.

To analyze to a high level of accuracy the resulting maps against the validation set of groundtruthed data.

Factors to consider:

- Choices of satellite image sensor and platform. Three aspect need to be considered in this context: (1) spatial resolution; the smallest sized earth feature recognized by the satellite sensor; (2) spectral resolution: maximum variations of the earth's reflectance recorded by the satellite sensor; and (3) temporal resolution: required time for a satellite image to repeatedly record the same place on the earth's surface.
- Seasonal variation of spectral values caused by the acquisition time of the satellite image.
- Time series interval.

- Cloud cover of satellite image.
- Variations in land cover within the area of interest.
- Image interpretation method and required software.
- Skill and experience of image interpreter.
- Interpreter familiarity with ground situation and availability of groundtruthed data.
- Land cover classification scheme.

Pre-requisite data:

- Time series satellite images.
- Thematic maps: elevation, slope, soil, accessibility, among others.
- Groundtruthed data.

Steps:

- Decide on the method and software to use in the image pre-processing and image interpretation.
- Satellite image pre-processing: geometric and atmospheric correction. Geometric correction aims to rectify geometric distortion in the satellite image caused by the satellite image recording process, while atmospheric correction aims to normalize seasonal variability in spectral values.
- Image interpretation and classification. In general, the two options of image interpretation are: (a) manual interpretation, where spectral signature labeling is conducted through visual inspection; and (b) automatic interpretation, where spectral labeling is conducted through a computer-aided algorithm.
- Accuracy assessment of classified images. This step is conducted to assess the quality of the interpretation process.
- Area calculation of each land cover type within the layers of strata/zones.

Output:

- Time series of land cover maps (Figure 34).
- Map of changes (Figure 35).

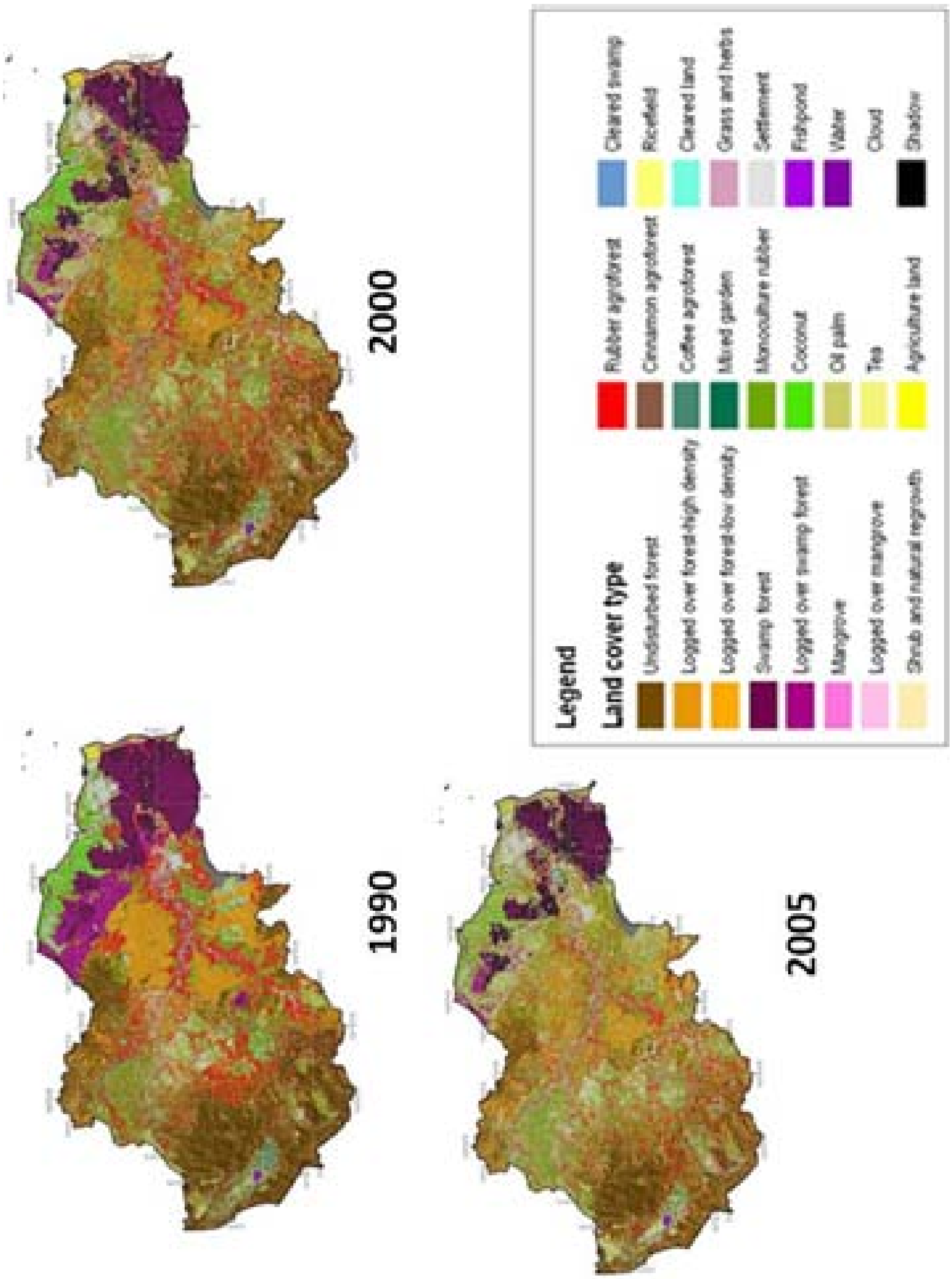


Figure 34. Example of time series land cover maps, Bungo, Jambi, Indonesia.

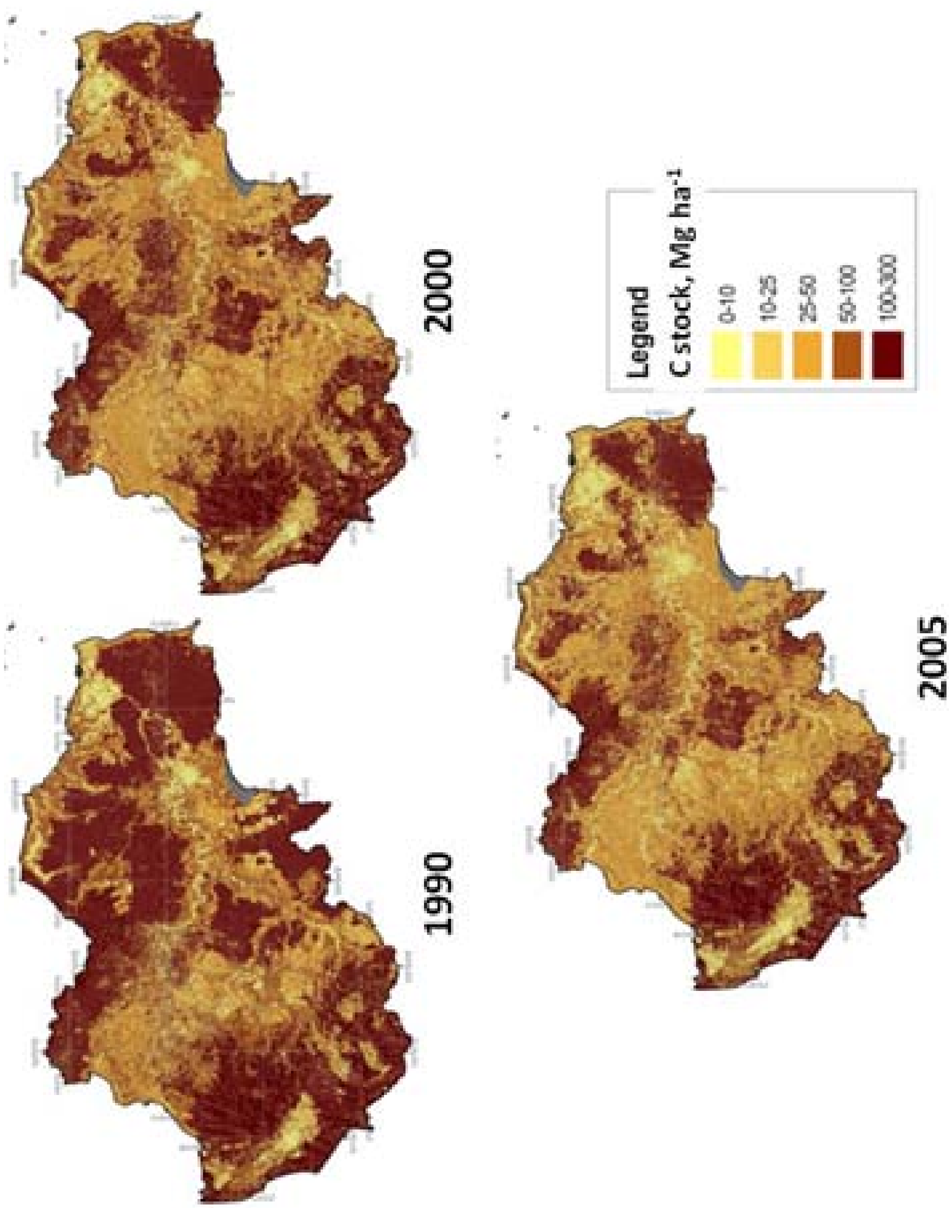


Figure 35. Example of change maps Jambi, Sumatra, Indonesia.

2.8.3. Change analysis

Areas of change for each possible transition between land cover types over time are calculated from the time series of wall-to-wall land cover maps that completely cover the region of interest. These areas are calculated within each stratum/zone of abiotic and management type layers. This should follow a straightforward series of technical steps involving satellite image interpretation and spatial analysis. The output is a LU/LC transition matrix of size n × n, where n is the number of LU/LC types (Table 6).

Table 6. Example of LU/LC transition matrix (hypothetical).

2000\2005	Primary forest	Seconday forest	Primary mangrove forest	Pine	Tree crop	Coconut	Complex AF	Simple AF
Primary forest	0.054	0.108	0.027	0	0.0027	0.02484	0.0081	0.0162
Seconday forest	0	0.12	0.048	0.008	0.02	0.04	0.04	0.04
Primary mangrove forest	0	0	0	0	0	0	0	0
Pine plantation	0	0	0	0	0	0	0	0
Tree crop	0	0.01	0.01	0.01	0.021	0.03	0.005	0.01
Coconut	0	0.03	0.013	0.001	00.001	0.02	0.01	0.02
Complex AF	0	0	0	0	0	0	0	0
Simple AF	0	0	0	0	0.01	0.015	0	0.018

2.9. Step 6: Upscaling

Combining data on the vectors of time-averaged C stocks for all land use classes used with the matrix of land cover change is now a matter of algebra and spreadsheets (Figure 37). There are a number of ways of visualizing and expressing the data as either maps, or in diagram or table formats, with each method having its own strengths and weaknesses as a tool for communication. When the net impacts on CO_2 emissions become known, the policy debate tends to shift towards 'who to blame' and 'who has to pay' aspects, which may give stakeholders reasons to use data selectively.

The previous steps have produced the following:

- At least two time series of land use/cover maps.
- Zonation.
- LU/LC transition matrix for each zone.
- Lookup table between LU/LC and LUS.
- Time-averaged C stock for each LUS for each zone.

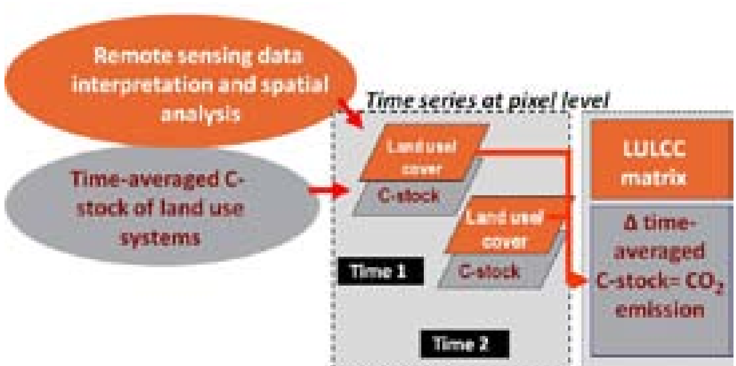


Figure 36. Upscaling process

There are a few simple calculations required to upscale from the plot level to the landscape level:

a. Land use/cover transition matrix in proportion (total sum is 1) for each zone by spatial analysis [dimensionless].

b. Proportion of each zone (total sum of the whole landscape is 1) by spatial analysis [dimensionless].

c. Total area of the whole landscape by spatial analysis [hectares].

d. Time-averaged C stock of each land use system calculated from the plot level measurements, allometric equations and statistical analysis (Mg ha^{-1} of C stock).

e. Changes in carbon stock for each transition by multiplying each cell in the matrix by the difference in the time averaged C stock for each transition/ conversion by the conversion factor (44/12) [Mg ha^{-1} of CO_2 equivalent].

f. Annual changes in carbon stock for each transition by dividing changes in carbon stock by the length of the study period (Mg ha^{-1} yr^{-1} of CO_2 equivalent).

g. Total annual emission and total sequestration and net changes of carbon stock in the landscape (Mg yr^{-1} of CO_2 equivalent).

h. Proportion of emissions and sequestration resulted by each transition (dimensionless or percent).

i. Carbon density map by spatial analysis (Mg ha^{-1} CO_2 equivalent).

j. Carbon emission map by spatial analysis (Mg ha^{-1} yr^{-1} CO_2 equivalent).

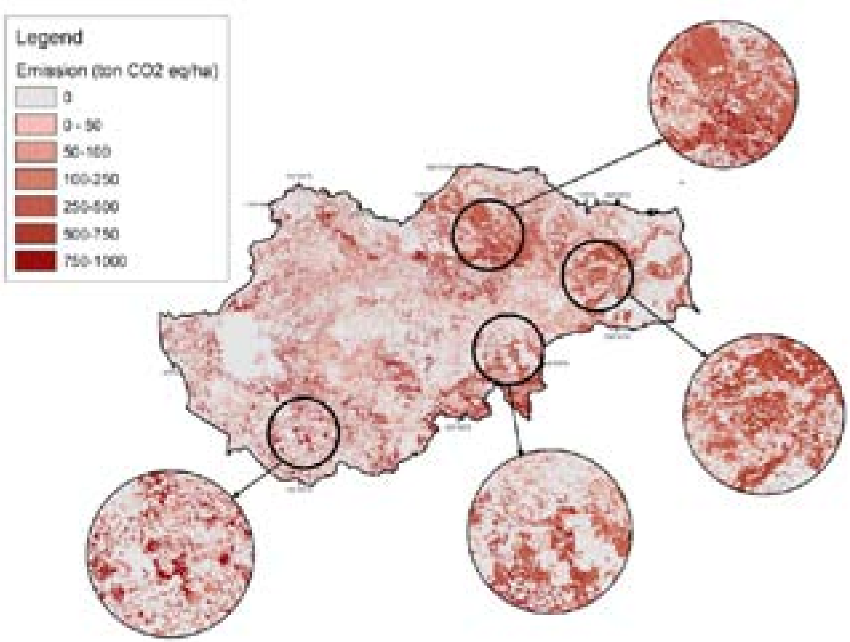


Figure 37. Sample of emission map, Jambi, Indonesia.

Case Study

photo: Kurniatun Hairiah

Agroforestry means growing and using useful trees and shrubs on farms and in the landscape in combination with annual crops, livestock and

Case study. ESTIMATION OF CARBON STOCK CHANGES IN KALIKONTO WATERSHED, MALANG (INDONESIA) USING RAPID CARBON STOCK APPRAISAL (RACSA) (Source: Hairiah *et al*., 2010)

The impacts of a change in land use from natural forest to a tree-based agricultural system on the net sequestration of CO_2 or the release of CO_2 to the atmosphere was rapidly estimated by measuring the change of carbon (C) stocks for a period of time using RaCSA (Rapid Carbon Stock Appraisal). The aim of this study was to assess the changes in aboveground C stock at the landscape level after forest conversion to various types of land use systems. Land cover change analysis was conducted on Landsat images using post classification comparison methods where information of change from 1990 to 2005 was derived from land cover maps of the Kalikonto watershed (Malang, East Java, Indonesia). The data showed that within 15 years (from 1990 to 2005), the area of natural forest had decreased 33% from 7269.93 ha in 1990 to 4852.26 ha in 2005; the annual forest conversion rate was about 2.2% (Figure 38). On the other hand, the total area of annual crops and settlements had increased by 45% and 18%, respectively, while the area of tree plantation and agroforestry had reduced by about 10%.

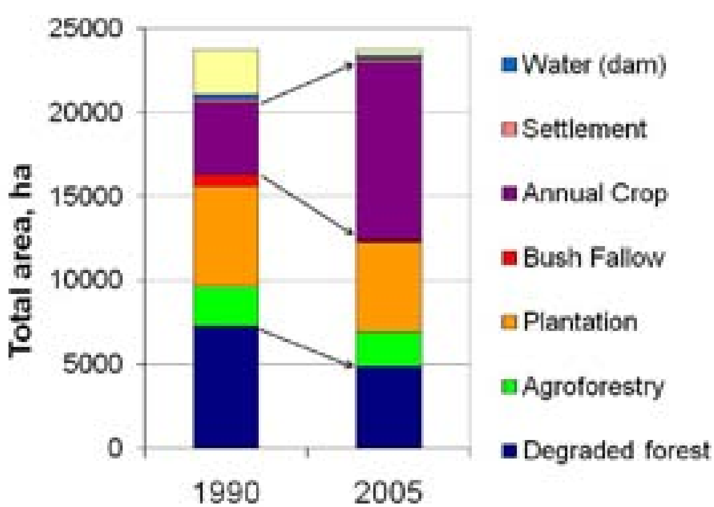


Figure 38. Land cover changes from 1990 to 2005 in Kalikonto watershed Malang, Indonesia based on analysis of land cover maps.

To estimate the change in the C stock at the plot level, measurements of all components of the C stock were made from June to December 2008 in upstream parts of the Kalikonto watershed covering a range of land use systems (LUS). The eight LUS most commonly found in the study area were: (degraded) natural forest; bamboo forest; three types of plantation: namely, pine (*Pinus mercusii*), mahogany (*Swietenia mahogany*) and 'damar' (*Agathis sp*.); multistrata shaded coffee with fruit and timber trees as well as nitrogen-fixing shade trees (mostly *Gliricidia sepium*); single shade coffee (shade tree *Gliricidia sepium*); and annual cropping systems (napier grass, vegetable and other food crops).

The results showed that natural forest in the Kalikonto area has been severely disturbed as indicated by a low total C stock of about 161 Mg ha^{-1}. The total C stock in the coffee-based agroforestry systems was lower, ranging from 99 to 111 Mg C ha^{-1} (Figure 39 and Table 7), while for the tree plantations (pine, mahogany, and damar mostly aged 25–40 years) the C stock ranged from 159 to 198 Mg C ha^{-1}.

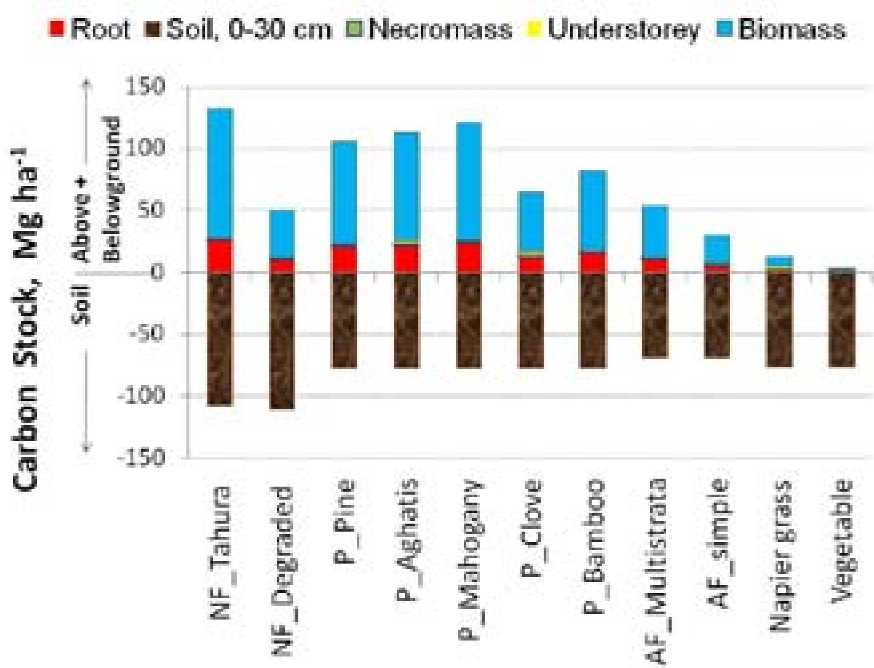


Figure 39. Total C stock in Kalikonto watershed, Malang, Indonesia of different componens of various land use types: degraded natural forest; coffee-based agroforestry (Multistrata and simple agroforestry); plantation (pine, agathis, mahogany, clove and bamboo); napier grass; and annual crops (mainly vegetables)

The time-averaged C stock was calculated to reflect the dynamics of C that is present in each land use system over its life span, which depend on the rate of C accumulation, the minimum and maximum amounts of C stored by each system, the time required to reach the maximum value and the rotation time. The time-averaged C stock of tree plantations was calculated based on average of C stocks of various types and ages of plantation (pine, agathis, mahogany, clove, and bamboo mostly) it was to be 139 Mg C ha^{-1} (Table 7), agroforestry was 111 Mg ha^{-1}, while for annual crops it was only 79 Mg ha^{-1}. The volcanic soils of the Kalikonto area (mostly Andisols and Inceptisols) contribute C stock of about 40–70 % to the total C stock of each land use, which is higher than earlier C stock soil data used based on Ultisols (generally applied to Sumatra) of around only 10–20%.

Table 7. Carbon stock of various components of different land use types in Kalikonto watershed Malang, Indonesia.

Land Cover	Land Use System	Plant Density per ha	Above ground Biomass	Estimated Root Biomass	Under story	Necro mass	Soil, 0-30 cm	Total C stock	Max. Age, year	Time- Avg. C Stock, Mg ha^{-1}
			Mg ha^{-1}							
Forest	Degraded Forest	2248	38.4	9.60	0.15	2.15	111	161	50	161
Agroforestry	AF_ Multistrata	3970	42.1	10.5	0.14	1.29	69	123	30	111
	AF_Simple	4018	21.4	5.3	0.91	2.33	69	99	30	
Plantation	Pine, 24 yr	795	82.6	20.7	1.22	1.59	77	183	30	144
	Agathis		87.5	21.9	2.67	1.34	77	190	40	146
	Mahogany	963	95.2	23.8	0.69	1.54	77	198	50	212
	Clove		47.3	11.8	1.53	4.15	77	142	35	70
	Bamboo	3188	63.9	16.0	0.40	2.20	77	159	15	121
Grassland	Napier grass, 4 months	-	15.0	3.7	4.41	1.02	76	100	0.25	89
	Napier grass, 1 month	-	0.9	0.2	0.21	0.53	76	78		
Annual crop	Vegetables	-	1.8	0.4	0.68	0.55	76	79	0.25	79

Napier grass = *Pennisetum purpureum* (Local name: Rumput Gajah)

Extrapolation of C stock from plot to landscape.

The geographical distribution of forest conversion and thus C stock reduction was mainly in the areas of high forest conversion in the far north of Pujon district covering the five villages of Pandesari, Wiyurejo, Madiredo, Tawangsari and Ngabab (Figure 40), while in the south, this area included three villages in the Pujon district (Pujon, Sukomulyo and Bendosari) and three villages in Ngantang District (Purworejo, Sidodadi, and Banjarejo).

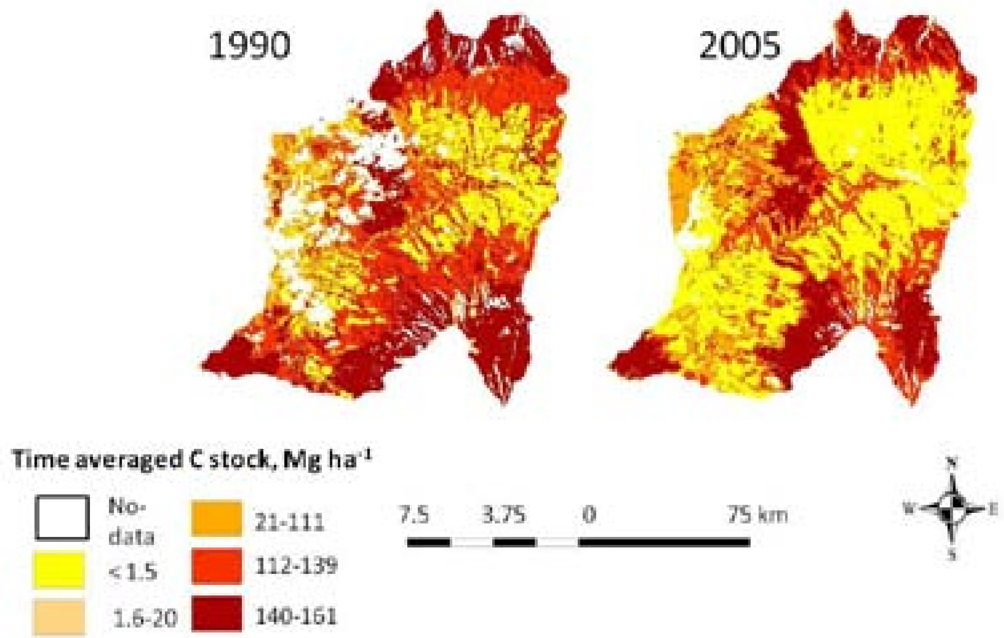


Figure 40. Distribution of carbon density in Kalikonto watershed Malang, Indonesia in 1990 and 2005.

Extrapolation of C stock from the plot level to the watershed level was calculated by multiplying the area of each land cover by its time-averaged aboveground C stock (see Table 6). Within 15 years, C lost from the whole watershed (20,856 ha) was estimated to be 352,963 Mg C yr^{-1} or the equivalent to a C loss of 1.03 Mg C ha^{-1} yr^{-1} or 3.76 Mg CO_2 ha^{-1} yr^{-1} (Table 7). The highest C lost in the study area was related to the land use trajectory of natural forest with about 10,598 Mg C ha^{-1} (49% of total lost), while from timber plantations and agroforestry it was about 11,947 Mg C ha^{-1} (56%) and 986 Mg C ha^{-1} (5%), respectively.

Table 8. Summary of results of estimation of C emission or sequestration related to land cover change in Kalikonto watershed Malang, Indonesia from 1990 to 2005.

Area, ha	20,855.88
Emission , Mega ton (M t)	0.35
Sequestrasion, M t	0.03
Net emission, M t	0.32
C rate of emission, Mg ha^{-1}	15.4
C factor emission, Mg ha^{-1} yr^{-1}	1.03
CO_2 factor emission, Mg ha^{-1} yr^{-1}	3.76

Planting more trees (damar, pines, mahogany) in the landscape through the Reforestation Program of the Forest Estate (PERHUTANI) in the period from 1990 to 2005 was not able to reduce the C lost from the landscape. Planting more trees in the landscape through agroforestry and plantation expansion may compensate for lost C through forest conversion.

photo: Kurniatun Hairiah

When forest resources such as timber, rattan, latex, fruits, vegetables, spices and medicinal become scarce or inaccessible in the natural forest, farmers can include them in their garden in agroforestry systems, which may hold as much carbon as is stored in secondary forests of similar age

References

Agus F, Subiksa I G M, 2008. Lahan Gambut: Potensi untuk pertanian dan aspek lingkungan (Peatland: Potential for agriculture and the environmental aspects). Indonesian Soil Research Institute and World Agroforestry Centre, Bogor. 36 pp.

Agus F, Yustika RD, Haryati U. 2007. Penetapan berat volume tanah (Soil bulk density determination). pp 25–34 In Sifat Fisik Tanah dan Metode Analisisnya. Balai Penelitian Tanah, Bogor.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Folster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H,; Puig H, Riera B and YamakuraT. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99. DOI 10.1007/s00442-005-0100-x.

Cossalter C and Pye-Smith C. 2003. Fast-Wood Forestry: Myths and Realities. Centre for International Forestry Research, CIFOR, Bogor.

http://www.cifor.org/publications/pdf_files/Books/ForestPerspective.pdf

Gibbs HK, Brown S, Niles JO, Foley JA. 2007. Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. Environ Res Lett 2:1–13.

Hairiah K, Ekadinata A, Sari R R, Rahayu S. 2011. Petunjuk praktis Pengukuran cadangan karbon dari tingkat plot ke tingkat bentang lahan. Edisi ke 2. World Agroforestry Centre, ICRAF Southeast Asia and University of Brawijaya (UB), Malang, Indonesia ISBN 978-979-3198-53-8. 90 pp.

Hairiah K, Sitompul SM, van Noordwijk M and Palm CA. 2001. Carbon stocks of tropical land use systems as part of the global C balance: effects of forest conversion and options for 'clean development' activities. ASB_LN 4A. and 4B.

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

Houghton RA. 2005. Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945–958.

Hue AX, Chen GX, Wang ZP, Van Cleemput O, Patrick Jr. WH. 2000. Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. Soil Sci. Soc. Am.J 64: 2180-2186.

IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by The National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds.). Published by IGES, Japan.

Jauhiainen J, Vasander H, Jaya A, Takashi I, Heikkinen J, Martikinen P. 2004. Carbon balance in managed tropical peat in Central Kalimantan, Indonesia. In Wise Use of Peatlands - Proceedings of the 12th International Peat Congress, 06.-11.06.2004, Tampere, volume 1, Päivänen, J. (ed.), International Peat Society, Jyväskylä, pp. 653–659.

Joosten H. 2007. Peatland and carbon. pp. 99–117 In Parish, F., Siri, A., Chapman, D., Joosten H., Minayeva, T., and Silvius M (eds.) Assessment on Peatland, Biodiversity and Climate Change.Global Environmental Centre, Kuala Lumpur and Wetland International, Wageningen.

Maltby E, Immirzi P. 1993. Carbon dynamics in peatlands and other wetland soils. Regional and global perspectives. Chemosphere 27(6), 999–1023.

MartinF S 2008. Using native timber trees for recovering degraded landscapes in the Philippines: Social, biophysical and economic assessment of agroforestry systems practiced by smallholder farmers. Doctoral thesis. Cordoba University, Madrid, Spain. 149 pp.

Melling L, Hatano R, Goh K J. 2005. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus (2005), 57B, 1–11.

Murdiyarso D, van Noordwijk M, Wasrin UR, Tomich TP and Gillison A N. 2002. Journal of Vegetation Science. 13 (3): 429-438.

Nogueira EM, FearnsidePM, Nelson, BW and Mabiane Batista França MB. 2007. Wood density in forests of Brazil's 'arc of deforestation': Implications for biomass and flux of carbon from land use change in Amazonia. Forest Ecology and Management 248:119–135.

Palm CA, van Noordwijk M, Woomer PL, Alegre J, Arevalo L, Castilla C, Cordeiro DG, Hairiah K, Kotto-same J, Moukam A, Parton WJ, Ricse A, Rodrigues V and Sitompul SM. 2005 Carbon losses and sequestration following land use change in the humid tropics. In: CA Palm, Vosti S A, Sanchez P A and P J Ericksen (eds.) Slash and Burn: The Search for Alternatives. Columbia University Press, New York, USA. pp 41-63.

Rügnitz M T, Chacón M L. 2009. Porro R. Guía para la Determinación de Carbono en Pequeñas Propiedades Rurales. 1. ed. Lima, Perú: Centro Mundial Agroflorestal (ICRAF) / Consórcio Iniciativa Amazônica (IA). 2009. 79 p.

Seng OD. 1990. Berat Jenis dari Jenis-jenis Kayu Indonesia dan Pengertian Beratnya Kayu untuk Keperluan Praktek (Specific Gravity of Indonesian Woods and its Significance for Practical Use). Pengumuman No. 46 (1951). Pusat Penelitian dan Pengembangan Hasil Hutan (Forest Product Research and Development Centre), Departemen Kehutanan, Bogor, Indonesia. 234p.

Smit AL, Bengough AG, Engels C, van Noordwijk M, Pellerin S and Van der Geijn (Eds.) 2000. Root Methods, a Handbook. Springer Verlag, Berlin. 587 pp

Suganda H, Rachman A, Sutono S. 2006. Petunjuk pengambilan contoh tanah (Guidance for sampling technique). pp. 3-24 In Sifat Fisik Tanah dan Metode Analisisnya. Balai Penelitian Tanah, Bogor.

van der Werf GR, Morton DC, DeFries RS, Olivier JGJ, Kasibhatla PS, Jackson RB, Collatz GJ and Randerson JT. 2009. CO_2 emissions from forest loss. Nature Geoscience 2, 737–738.

van Noordwijk M and MuliaR. 2002. Functional branch analysis as tool for fractal scaling above- and belowground trees for their additive and non-additive properties. Ecol. Model. 149, 41–51.

van Noordwijk M. and Purnomosidhi P. 1995. Root architecture in relation to tree-soil-crop interactions and shoot pruning in agroforestry. Agrofor. Syst. 30, 161–173.

van Noordwijk M, Lawson G, Groot JJR, Hairiah K, 1996. Root distribution in relation to nutrients and competition. In: C.K. Ong and P.A. Huxley (Eds.). Tree-Crop Interactions - a Physiological Approach. CAB International, Wallingford. pp 319-364

van Noordwijk M, Lusiana B, and Khasanah N. 2004. WaNuLCAS version 3.1, Background on a model of water, nutrient, and light capture in agroforestry systems. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia. 246 pp.

van Noordwijk M, Spek LY, and De Willigen P. 1994. Proximal root diameter as predictor of total root size for fractal branching models I. Theory. Plant Soil 164, 107–117.

van Noordwijk M, Williams S E and Verbist B (Eds.) 2001.Towards integrated natural resource management in forest margins of the humid tropics: local action and global concerns. ASB-Lecture Notes 1 – 12. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia. Also available from: http://www.icraf.cgiar.org/sea/Training/Materials/ASB-TM/ASB-ICRAFSEA-LN.htm

Walkley A and Black T A. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed of modification of the chromic acid titration method. Soil Sci. 37: 29-38.

Wösten JHM, Ismail AB, van Wijk ALM. 1997. Peat subsidence and its practical implications: A case study in Malaysia. Geoderma 78:25–36.

Attachments: data recording sheets

http://www.worldagroforestry.org/sea/Products/AFDbases/AF/index.asp

photo: Kurniatun Hairiah

Participants in a RACSA training in Vietnam learn the basics of recording tree diameter at standardized height (1.3 m) in an agroforestry system on a steep slope

Glossary

These definitions are provided solely for the purposes of this Manual. Words underlined in blue are linked to webpages providing additional information.

Activity data

Data on the magnitude of a human activity resulting in emissions or removals taking place during a given time period. Examples of activity data are: data on energy use, metal production, land areas, management systems, lime and fertilizer use and waste arising.

Agroforestry

The simple definition of Agroforestry is planting trees on farm or tree based farming. The World Agroforestry Centre, ICRAF define Agroforestry as a collective name for land-use systems and practices where woody perennials are deliberately integrated with crops and/or animals on the same land management unit. The integration can be either in spatial mixture or temporal sequence. There are normally both ecological and economic interactions between the woody and non-woody components in agroforestry (http://www.fao.org/wairdocs/TAC)

Biomass

Biomassis a vegetation attribute that refers to the weight of plant material within a given area. Another commonly used term for biomass is production which refers to how much vegetation is produced on an area. It usually expressed as dry weight in g m^{-2} or kg ha^{-1}.

Carbon budget

The balance of the exchanges of carbon between carbon pools or within one specific loop (for example, the atmosphere-biosphere) of the carbon cycle.

Carbon dioxide equivalent

A measure used to compare different greenhouse gases based on their contribution to radiative forcing. The UNFCCC (2005) currently uses global warming potentials (GWPs) as factors to calculate the carbon dioxide equivalent.

Carbon stocks

Total carbon stored (absolute quantity) in terrestrial ecosystems at a specific time as living or dead plant biomass (aboveground and belowground) and in the soil, along with usually negligible quantities as animal biomass. The unit is Mg ha^{-1}.

Carbon pool

A reservoir or a system which has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, soils and the atmosphere. The units are kg ha^{-1} or Mg ha^{-1}.

Charcoal

The blackish porous residue, consisting of impure carbon (about 85–90% C) obtained by removing water and other volatile constituents of animal and plants substances. It is usually produced by heating wood in the absence of oxygen.

Country-specific data

Data for either activities or emissions that are based on research carried out on sites either in that country or otherwise representative of that country.

Emissions

The release of greenhouse gases and/or their precursors into the atmosphere over a specified area and period of time. (UNFCCC Article 1.4)

Forest

See Box 8

Good Practice

A set of procedures intended to ensure that greenhouse gas (GHG) inventories are accurate in the sense that they are systematically neither overestimates nor underestimates so far as can be judged, and that uncertainties are reduced as far as possible.

Good Practice covers the choice of estimation methods appropriate to national circumstances, quality assurance and quality control at the national level, quantification of uncertainties and data archiving and reporting to promote transparency.

Mortality/ Tree mortality

Mortality rate of tree is the total deaths tree relative to total population in a specified area over specified period of time. Usually it is expressed in units of death per 1.000 trees per year. Thus, annually a mortality rate 5.5 in a population of 10.000 tree per ha, that means 55 death tree per year or 0.55% out of the total tree population density.

Necromass or Dead Organic Matter

The weight of dead organisms, usually expressed as g m^{-1} or kg ha^{-1}. Necromass consists mainly of plant litter. It is usually on the soil surface or in the soil but some may take the form of standing or attached dead material. Much of the transience or lag in the response to rapid climate change by forest ecosystems can be estimated by the difference between tree regeneration (tree natality) and tree mortality. Annual necromass increments result from individual tree mortality within stands and from larger-scale disturbance and dieback events (fires, insect infestations, disease infestations, wind throw). In addition, a significant portion of the carbon stocks which comprise stored terrestrial carbon of forest and non-forest communities is in the form of necromass.

Organic matter (or organic material)

Organic matter is anything that contains carbon compounds which is formed by living organisms such as stems, branches, leaves, flowers, fruits, any parts of animals, manure, droppings, microbes and macrobes, sawdust etc.

Regeneration or Natality

The renewal of a stand of trees through either natural means (seeded onsite or from adjacent stands, or deposited by wind, birds or animals) or artificial means (by planting seedlings or direct seeding).

Removals

Removal of greenhouse gases and/or their precursors from the atmosphere to a sink.

Organic matter (or organic material)

Matter that has come from a once-living organism, is capable of decay, or the product of decay, or is composed of organic compounds.

Soil organic matter (SOM)

The organic matter component of soil exclusive of the material that has not decayed. It can be divided into three general pools: living biomass of microorganisms, fresh and partially decomposed residues and humus: humus (the well-decomposed organic matter and highly stable organic material). Surface litter is generally not included as a part of soil organic matter. It is expressed in % C.

Sequestration

The process of removing carbon from the atmosphere and stored it in a reservoir. Or it can also be called as removal of CO_2.

Sink

Any process, activity or mechanism which removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere. (UNFCCC Article 1.8) Notation in the final stages of reporting is the negative (-) sign.

Source

Any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere. (UNFCCC Article 1.9) Notation in the final stages of reporting is the positive (+) sign.

Standing litter

The amount of litter weight at a given time. Usually refers to the amount of litter found on the soil surface.

Understory

Any plant growing under the canopy formed by other plants, particularly herbaceous and shrub vegetation under a tree canopy.

Wood density

The weight of a given volume of wood that has been air-dried. Wood density is technically defined as the ratio of the oven-dry mass of a wood sample divided by the mass of water displaced by its green volume (wood specific gravity, or WSG). Usually it is expressed as kg dm^{-3}. The density of the wood in a tree indicates how much carbon the plant has allocated into construction costs. Wood density varies within the plant, during the life of the plant and between individuals of the same species. Also, the branches and the outer part of the trunk tend to have lighter (less dense) wood than the pith.

Wetland

Land where an excess of water is the dominant factor determining the nature of soil development and the types of animals and plant communities living on the soil surface. It spans a continuum of environments where terrestrial and aquatic systems intergrade.

Peatland

Peat is intrinsic to many wetlands around the world. Peat is partly decomposed plant remains that consist of more than 65% organic matter (dry weight). Moss, grass, herbs, shrubs and trees may contribute to the buildup of organic remains, including stems, leaves, flowers, seeds, nuts, cones, roots, bark and wood. Through time, the accumulation of peat creates a substrate, influences ground-water conditions and modifies the surface morphology of the wetland.

Prefixes and multiplication factors

Multiplication Factor	Abbreviation	Prefix	Symbol
1 000 000 000 000 000	10^{15}	peta	P
1 000 000 000 000	10^{12}	tera	T
1 000 000 000	10^{9}	giga	G
1 000 000	10^{6}	mega	M
1 000	10^{3}	kilo	k
100	10^{2}	hecto	h
10	10^{1}	deca	da
0.1	10^{-1}	deci	d
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	µ

Conversion Units and abbreviations

1 tonne (t)	1000 kg	10^{6} gram (g)	1 Megagram (Mg)
1 Megatonne (Mt)	1,000,000 t	10^{12} g	1 Teragram (Tg)
1 Gigatonne (Gt)	1,000,000,000 t	10^{15} g	1 Petagram (Pg)
1 hectare (ha)	10,000 square meter (m^2)		
1 square kilometer (km^2)	100 hectare (ha)		
1 tonne per hectare (t ha^{-1})	100 gram per square meter (g m^2)		
1 tonne carbon	3.67 tonne carbon dioxide (t CO_2)		
1 tonne carbon dioxide	0.273 tonne carbon (t C)		
1 tonne	0.984 imperial ton	1.10 US ton	2204 pound
1 hectare (ha)	2.471 acre		c
1 square kilometer (km^2)	0.386 square mile		m
1 tonne per hectare (t ha^{-1})	892 pound per acre		µ

WORKSHEETS

photo: Kurniatun Hairiah

Trees inside and outside the forest enhance carbon uptake and storage in (agro)ecosystems for a long time

Work sheet 1A

BIOMASS of BIG TREES (diameter >30 cm) – nondestructive measurements

Site number :..................
Name of village :.................
Land Use Type :....................
Location (GPS) : .... E, ... S
Farmer name : ....
Sample area : 20 m × 100 m = 2000 m^2
Sample taken by : ....
Date : ....
How long ago was the plot used
for agriculture and how? ....

No	Local/ Scientific name	Branched? Y/N	G	D	H	ρ*)	Biomass, kg/tree **)	Note
1							....	
2							....	
3							....	
4							....	
...							....	
100							....	
	TOTAL TREE BIOMASS						....	

Note:

G=girth, cm, D = *DBH*= G/π, cm where π =3.14 ; H= tree height, cm,
ρ = Wood density, g cm^{-3}

*)Estimated wood density: High, Medium, Low (0.75, 0.5, 0.2 g cm^{-3})[2]

**) Estimate AGB using specific allometric equations for trees growing in tropical forest (see Table 4), and for trees growing in agroforestry and plantation systems (see Table 5)

[2] Based on the average value of wood density classification developed by Seng (1990)

Work sheet 1B

BIOMASS of SMALL TREES (5 cm < diameter < 30 cm) – nondestructive measurements

Site number :..................

Name of village :.................

Land Use Type :...................

Location (GPS) : .... E, ... S

Farmer name : ....

Sample area : 5 m x 40 m = 200 m^2

Sample taken by : ....

Date : ....

How long ago was the plot used

for agriculture and how? ....

No	Local/ Scientific name	Branched? Y/N	G	D	H	ρ*)	Biomass, kg/tree **)	Note
1							....	
2							....	
3							....	
4							....	
...							....	
100							....	
						TOTAL TREE BIOMASS	....	

Note:

G=girth, cm, D = *DBH*= G/π, cm where π =3.14 ; H= tree height, cm,
ρ = Wood density, g cm^{-3}

*)Estimated wood density: High, Medium, Low (0.75, 0.5, 0.2 g cm^{-3})[2]

**) Estimate AGB using specific allometric equations for trees growing in tropical forest (see Table 4), and for trees growing in agroforestry and plantation systems (see Table 5)

[2] Based on the average value of wood density classification developed by Seng (1990)

Work sheet 2

BIOMASS of UNDERSTORY – destructive measurements

Site number :..................

Name of village :.................

Land Use Type :...................

Location (GPS) : .... E, ... S

Farmer name : ....

Sample taken by : ....

Date : ....

Subplot size : 0.5m x 0.5m = 0.25 m^2

No.	Sample FW (kg)		Sub-sample FW (g)		Sub-sample DW (g)		Total Dry Weight	
	Leaf	Stem	Leaf	Stem	Leaf	Stem	g/0.25 m^2	g/m^2
1								
2								
3								
4								
5								
.....								
	Total							....

Calculations

Total dry weight (kg m^{-2})

$$= \frac{\text{Total fresh weight (kg) x Subsample dry weight (g)}}{\text{Subsample fresh weight (g) x Sample area (m}^2\text{)}}$$

Work sheet 3A

BIOMASS of DEAD BIG TREES – nondestructive measurements

Site number :..................
Name of village :.................
Land Use Type :...................
Location (GPS) : .... E, ... S
Farmer name : ....
Sample taken by : ....
Date : ....
Plot size : 20 x 100 m^2

No.	**G1 (cm)**	**G2 (cm)**	**G average (cm)**	**D (cm)**	H (cm)	**Estimated DW of necromass, kg**	**Note (stage of wood decomposition)**
1							
2							
3							
......							
......							
50							
					Total		

Calculations

For unbranched cylindrical structures, the equation is based on the volume of a cylinder:

$$\text{Biomass} = \pi D^2 \; H \rho / 40$$

where, biomass is expressed in kg, H = height/length (m), D = tree diameter (cm) and ρ = specific gravity (g cm^{-3}) of wood. The latter is estimated as 0.4 g cm^{-3} as a default value, but can be around 0.75 g cm^{-3} for dense hardwoods, around 0.2 g cm^{-3} for very light species, and generally decreases during the decomposition of dead wood laying on the soil surface.

Work sheet 3B

BIOMASS of DEAD SMALL TREES – nondestructive measurements

Site number :..................

Name of village :.................

Land Use Type :...................

Location (GPS) : .... E, ... S

Farmer name : ....

Sample taken by : ....

Date : ....

Plot size : 5 x 40 m^2

No.	G1 (cm)	G2 (cm)	G average (cm)	D (cm)	H (cm)	Estimated DW of necromass, kg	Note (stage of wood decomposition)
1							
2							
3							
......							
......							
50							
					Total		

Work sheet 3C

LITTER DRY WEIGHT – nondestructive measurements

Site number :..................
Name of village :.................
Land Use Type :....................
Location (GPS) : .... E, ... S
Farmer name : ....
Sample taken by : ....
Date : ....
Plot size : 0.5 x 0.5m = 0.25 m^2

No.	Total FW (kg)	Sub-sample FW (g)	Sub-sample DW (g)	Total DW fine litter		Total C, %	Total C stock, ton/ha
				kg/0.25 m_2	kg/m_2		
1							
2							
3							
4							
5							
6							
				Total DW	....		
				Avg. DW	....		

Calculations:

$$\text{Total DW(kg m-2)} = \frac{\text{Total FW (kg) x Sub-sample DW (g)}}{\text{Sub-sample FW (g) x Sample area (m}^2\text{)}}$$

$$= \text{DW (kg/ha) x 10} = \text{DW} \quad \text{Mg ha}^{-1}$$

Take the average of the 6 samples to record the litter biomass for the transect replicate.

Work sheet 4

Soil Carbon Stock

Site number :..................

Name of village :.................

Land Use Type :...................

Location (GPS) : .... E, ... S

Farmer name : ....

Sample taken by : ....

Date : ....

No.	LUS	Site	Soil depth, m	Soil Bulk density, kg dm-3	Total C, %	Total DW fine litter kg/0.25 m2
1						
2						
3						
4						
5						

APPENDIX

photo: Nina Dwi Lestari

Putting a volunteer farmer in a sack helps to explain to farmers on the forest edge how global warming works: the gasses released in burning fuel or the forest put another layer around the earth that makes us all hotter, just as the 'sacked' farmer experiences

Appendix. Climate change

What's happening with our climate?

Climate describes the weather at a location over a long time; a minimum recording period of 30 years is deemed necessary to account for normal variation. Even with such a definition, the earth's climate has changed throughout the history of the planet and it will continue to change. However, for the first time in geological history, a single species, humankind, is causing climate change. We live in the Anthropocene, the geological time period defined by human-induced climate change. Climate change means more than changes in the weather. It affects the environment that people, their crops, trees, forest and livestock as well as wild flora and fauna depend on. The United Nations Framework Convention on Climate Change (UNFCC) (http://unfccc.int/files/documentation/text/html/list_search.php?what=keywords&val=&valan=a&anf=0&id=10) in article 1 (2001) defines climate change as *"A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". However, the Intergovernmental Panel on Climate Change (IPCC) defines climate change more simply as "Any change in climate over time whether due to natural variability or as a result of human activity".*

According to the 4th assessment of the IPCC, released in 2007, evidence of global warming is unequivocal. Observed increases in global average air and ocean temperatures, widespread melting of snow and ice and rising of the global average sea level are among key points in the evidence. The year 2008 was the coolest year since 2000, but it was still the 10th warmest year on record since the beginning of instrumental climate records in 1850. Record holders are 2005, 2007, 1998, 2002, 2003 and 2004. The 100-year linear trend (1906–2005) is now estimated to be an increase of 0.74 °C [0.56– 0.92 °C] (Figure 41).

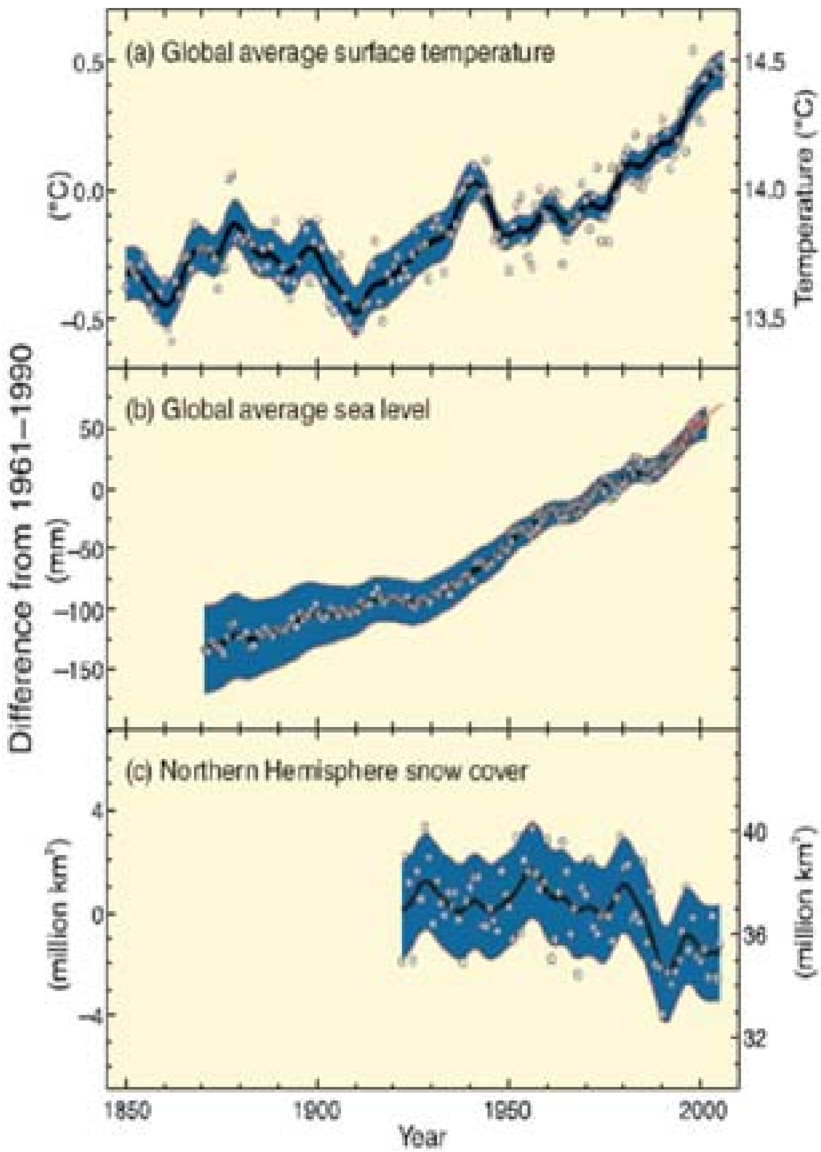


Figure 41. Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data; and (c) Northern Hemisphere snow cover for March–April. All differences are relative to corresponding averages for the period 1961–1990. Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). (IPCC WG1, 2007).

Is Global warming something we should worry about?

Are the consequences of an increase in temperature really all that bad? There are some who argue that an increase in temperature is actually a good thing in many parts of the world or that an increase in CO_2 concentration will promote plant growth and increase plant production. Is the increase likely to continue, stabilize or even reverse if we continue with whatever it is we are doing? Are there any further consequences on land management? The conclusion of the IPCC, based on input from a large numbers of scientists and public consultation is that by the time global warming reaches an increase of 2 ^{0}C, major shifts in oceanic circulation and other feedback systems can occur, which will cause major disruption to the world as we know it. Despite, locally positive effects on food production in the temperate and subarctic zone, the net effects on global food production and human health will be negative. By 2020, between 75 and 250 million people in Africa are projected to be exposed to increased water stress due to climate change. Freshwater availability in Central, South, East and Southeast Asia, particularly in the large river basins, is projected to decrease. By 2020, in some countries, yields from rain-fed agriculture could be reduced by up to 50%. In many African countries, agricultural production, including access to food, is projected to be severely compromised. In particular, the heavily populated megadelta regions in South, East and Southeast Asia will be at greatest risk due to increased flooding from the sea and, in some megadeltas, flooding from rivers. The cost of adaptation could amount to at least 5–10% of the total economy. There is good reason to take this seriously, and the remaining scientific uncertainty is no excuse for not acting now.

What causes global warming?

Changes in the global climate are primarily caused by changes in the composition of the atmosphere. The atmosphere influences the balance between incoming radiation from the sun and outgoing heat from the earth (Figure 43). Current understanding of global climate recognizes two major factors of natural variability in climate: the 11-year sunfleck cycle in the intensity of solar radiation and the episodic cooling effects due to volcanic eruptions that cause dust and sulfur dioxide to be projected into the atmosphere. On top of that, a number of effects are due to increased emissions of greenhouse gases and the direct effects of land cover on reflection (albedo). The dominant effect, however, is the increased emission of

greenhouse gases, with carbon dioxide (CO_2) being the main one (Figure 43). The main concern relates to greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Ironically, the control of air pollution caused by sulphur dioxide (SO_2) since the 1970s has probably increased global warming, as this pollutant has a net cooling effect. Human activity has led to the steady addition of CO_2 to the atmosphere and an increase in the atmospheric concentration from 285 ppmv (parts per million on a volume basis) before the Industrial Revolution of the 19th century to 379 ppmv in 2005.

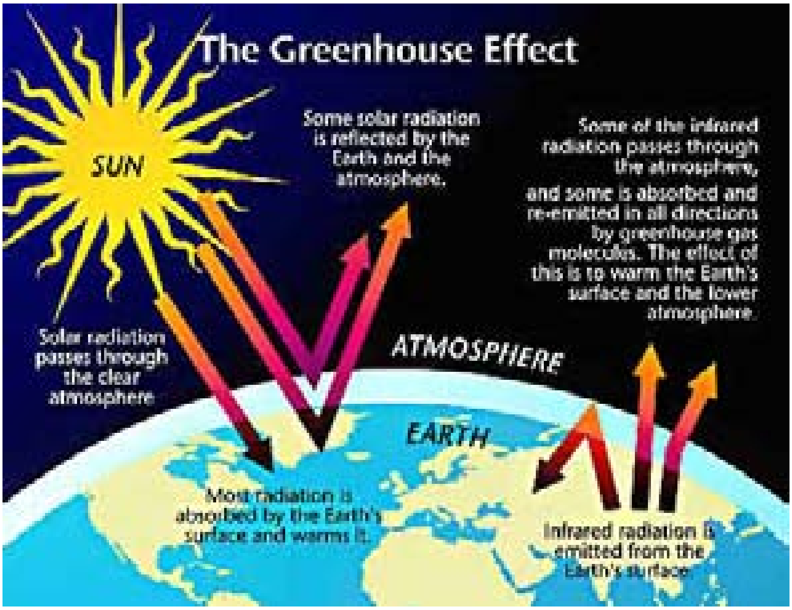


Figure 42. Illustration of solar radiation travelling through the atmosphere on its way to warm the earth's surface. This incoming energy is balanced by infrared radiation leaving the surface. On its way out through the atmosphere, this infra red is absorbed by greenhouse gases (principally water vapor, CO_2 and CH_4) that act as a 'blanket' over the earth's surface keeping it warmer. Increasing the amount of these gases increases the greenhouse effect and so increases the average temperature of the earth's surface (http://www.mtholyoke.edu/~sevci20l/images/Greenhouse%2520Effect.gif&imgrefurl).

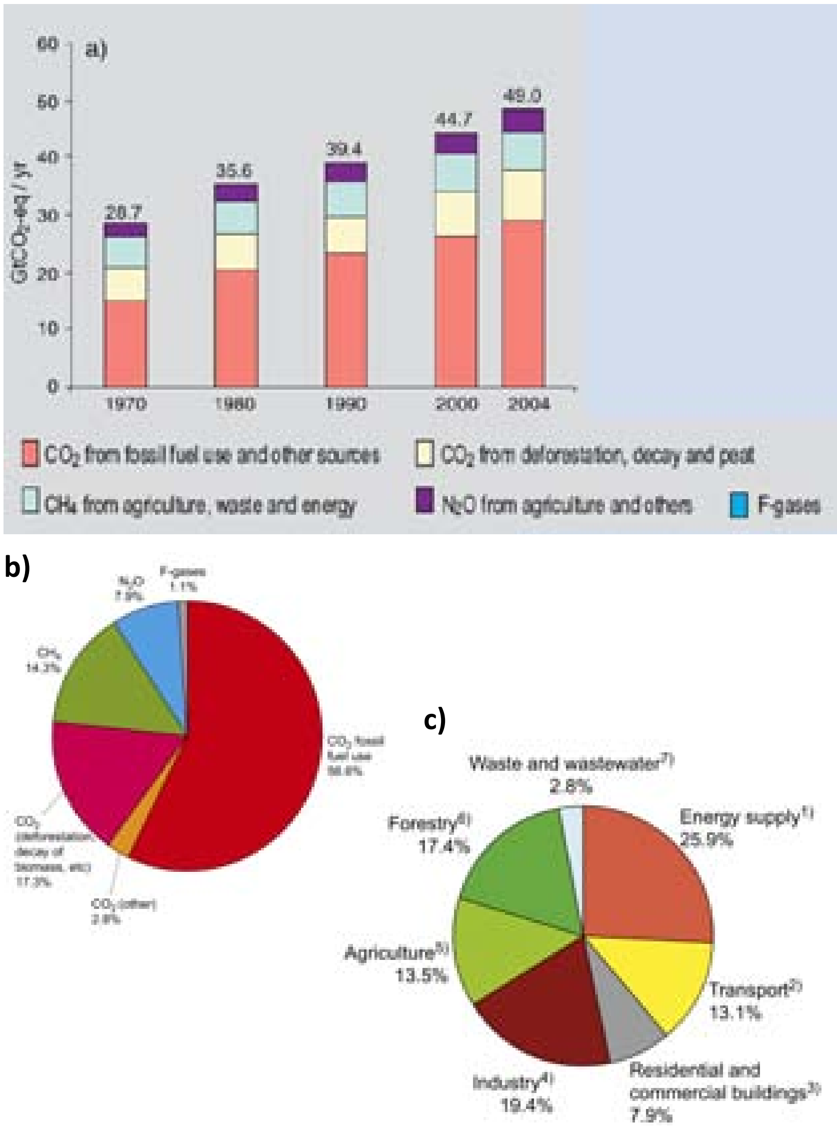


Figure 43. Global annual emissions of anthropogenic greenhouse gases (GHGs) from 1970 to 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-equivalents. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-equivalents. (Forestry includes deforestation) (IPCC, 2007) http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

Human activity and greenhouse gas emissions

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

Both releases from fossil fuel use and land use are part of the global cycle, that over geological timescales has made CO_2 a very rare and O_2 a very common gas in the global atmosphere. The current return to a higher CO_2 atmosphere is taking us back into the geological past. It won’t be the end of life on earth, but it will cause enough disruption to be a serious concern.

Balai Penelitian Tanah

World Agroforestry Centre
TRANSFORMING LIVES AND LANDSCAPES

ASB Partnership for the Tropical Forest Margins

ALLREDDI