Chapter 5. Carbon measurement of land uses

Objectives

1. Explain basic concepts of terrestrial carbon cycle and global carbon accounting systems,
2. Guide carbon analysis within a national accounting framework,
3. Introduce carbon measurement protocols and reference materials, using a bottom-up approach for carbon measurements from plot to land use, to landscape/sub-national level, and to national scale,
4. Identify data sources, gaps and measurement priorities,
5. Estimate ”typical carbon stock values” (time-averages) of land uses for use in an opportunity cost analysis.
6. Assess costs for capacity building based on available national capacities.

Contents

1. Numerous terms are used in the measurement of carbon. For definitions, please refer to the Glossary in **Appendix A**.

Forester and carbon specialist words

Allometric equation	Diameter at Breast Height (DBH)	Litterfall
Biomass	Humification	Landscape
Carbon dioxide flux		Necromass

Know your carbon

2. How much carbon would be emitted if a given hectare of forest were converted to another use? The answer to this question is a critical part of analyzing REDD+ opportunity costs. In this chapter, we first present basic concepts of terrestrial carbon (C) cycle and global carbon accounting systems. Next, we show how to estimate *typical carbon stock values* at sub-national and national levels. Important carbon measurement protocols and reference materials are presented along with how to identify data sources and carbon measurement priorities. Cost estimates for applying these methods are also provided.

Terrestrial carbon cycle

3. Carbon dioxide (CO_2) is exchanged between terrestrial vegetation and the atmosphere. Net balances change between sequestration (also known as storage or fixing) and release according to time period: (a) minute-to-minute (e.g., with cloud interception of sunlight), (b) day-night pattern, across a seasonal cycle of dominance of growth and decomposition, and (c) the lifecycle stages of a vegetation or land use system. Within this manual, we focus on the latter time scale, as part of annual (or 5-yearly) accounting of land use and land use change. At this time scale, many exchanges (or fluxes) can be expected to cancel out, thereby enabling a focus on net carbon changes.

Link this carbon analysis with on-going carbon MRV efforts

4. Carbon can take different paths. In most years, the annual net effect of photosynthesis, respiration and decomposition is a relatively small increment in stored carbon. Nevertheless, accumulated gains sometimes are lost in drought years where fire consumes organic matter. Carbon can also move off-site. Organic products (e.g., wood, resin, grain, tubers) leave the area of production and become part of trade flows, usually being concentrated in urban systems and their waste dumps. Only small amounts of stored carbon may leach out of soils and enter long-term storage pools in freshwater or ocean environments, or contribute to peat formation.

Deforestation and carbon balance

5. When forests are converted to other uses, a large net carbon release occurs into the atmosphere. The process can happen in a matter of hours, in case of fire; over a number of years, due to decomposition; or over decades, where wood products enter domestic/urban systems. The net emissions can be estimated by examining the decrease or increase in the 'terrestrial carbon stocks.' Since tropical forests in their natural condition contain more aboveground carbon per unit area than any other land cover type (Gibbs, et al., 2007), they are important to consider within effort to mitigate climate change.

6. Consistent accounting for all carbon inflows and outflows is more complex than a simple check of the bottom-line change in total global carbon stock. Current estimates stating that 'land use, land use change and forestry' (LULUCF) is responsible for 15-20% of total greenhouse gas emissions is based on this type of stock accounting. Net sequestration is occurring in temperate zones and large net emissions in the tropics. Tropical peat areas are particularly small source areas with high emission estimates (IPCC, 2006). For the purposes of estimating REDD+ opportunity costs, carbon measures of different land uses are required in order to estimate the carbon effects from numerous types of land use change.

Carbon is not just carbon

7. Carbon is found in different pools. Terrestrial carbon stocks of all carbon stored in ecosystems are in:

- Living plant biomass (above- and below-ground)
- Dead plant biomass (above- and below-ground)
- Soil (in soil organic matter and, in negligible quantities, as animal and micro-organism biomass)

8. In the IPCC guidelines, these pools are described as *above-ground biomass*, *below-ground biomass*, *dead wood and litter*, and *soil carbon*. These are summarized in Figure 5.1 described in more detail below.

Table 5.1. Four IPCC carbon pools

	Alive	*Dead*
Above ground	Biomass (, stems, branches leaves of woody and non-woody vegetation)	Wood and litter
Below ground	Biomass (roots, fauna)	Soil carbon (including peat)

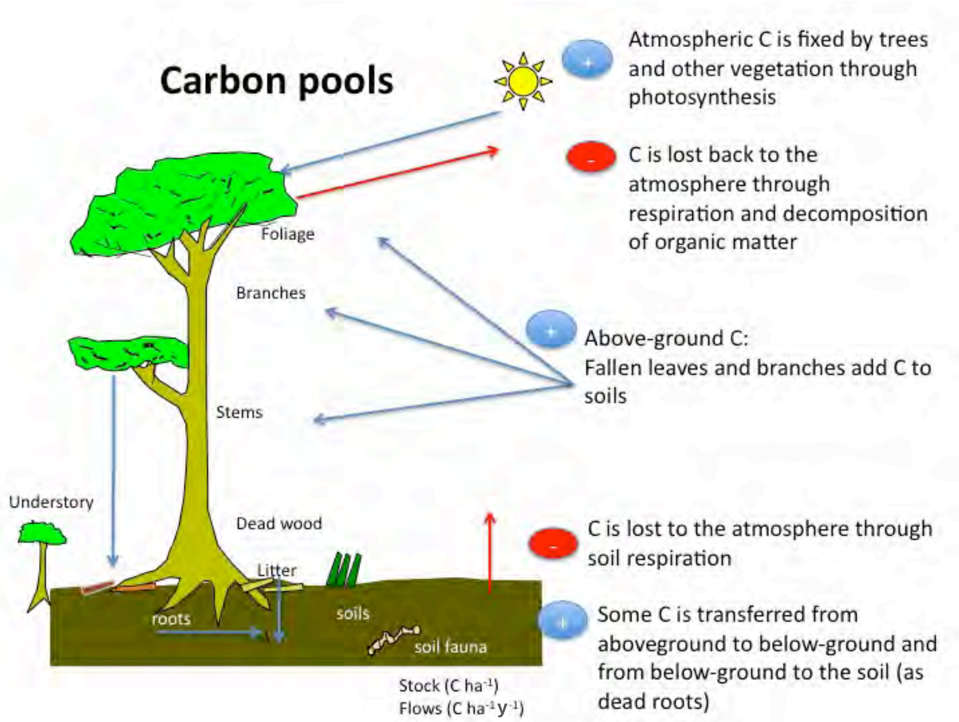


Figure 5.1. Terrestrial carbon pools

Source: Adapted from Locatelli (2007) and EPA (2009), by Honorio and Velarde (2009).

Living plant biomass carbon

9. *Above-ground 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 weeds.

10. *Below-ground biomass* comprises roots, soil fauna, and the microbial community.

Dead plant biomass carbon

11. The dead organic matter (i.e., necromass) includes fallen trees and stumps, other coarse woody debris, the litter layer and charcoal (or partially charred organic matter) above the soil surface. Carbon stock of litterfall in a tropical rain forest is typically about 5 tC /ha/yr, with a mean residence time in the litter layer of about 1 year. Dead trees may take about 10 years to decompose, and necromass is about 10% of total aboveground carbon stock in a healthy natural forest. Since logging tends to focus on harvesting the more valuable trees and damage many others, necromass may be 30-40% of the aboveground carbon stock after logging. If fire is used in land clearing, the resulting carbon will be emitted directly or reside for approximately a decade.

Soil Carbon

12. Soil carbon consists of organic carbon, inorganic carbon, and charcoal. Bicarbonate, an inorganic form of carbon, exists in calcareous soils, but is insignificant in neutral and acid

soils. The main form of soil carbon is in various stages of humification, with turnover times reaching up to 100's (or even 1000's) of years. In peat soils, turnover times can reach 1000's of years.

13. For mineral soils, the change in soil organic carbon is relatively small and mostly occurs in the top 30 cm of the soil layer (IPCC, 1997). Organic carbon concentration in soils generally decreases with depth, with a higher fraction of relatively stable pools accompanying the lower total carbon concentration. The strongest response of soil carbon stock to land cover change occurs in the top 20-30 cm. With empirical data, however, only changes in the layer 0-5 cm depth are often noticeable.

14. The change in soil carbon content due to land use change is rarely larger than 20 Mg carbon per ha (IPCC, 1997; Murty, et al., 2002), unless in wetland conditions. Under specific climatic conditions (e.g., with an annual rainfall surplus but a prolonged dry season in flat terrain with deep groundwater storage) trees with deep root systems are able to prolong the growing season. in addition, the turnover of fine roots at depth adds soil carbon stocks at depths that can lead to soil carbon changes after conversion in excess of 20 Mg carbon per ha. For example, when *Imperata* grassland is converted to oil palm plantation on mineral soil, an increase in soil carbon stock of as high as 13.2 ± 6.6 Mg /ha from the initial stock of 40.8 ± 20.4 Mg /ha can be expected (Agus, et al., 2009).

Box 5.1. Most of the biomass is in the few really big trees

The carbon stock in an individual tree depends on its size. Trees of 10-19 cm stem diameter (measured at standardized 1.3 m above the ground and called 'diameter at breast height' or DBH), may have a biomass of around 135 kg/tree. With approximately 900 trees per ha, the corresponding associated biomass is 121.5 t/ha. Yet, most of the biomass is in the few large trees. With a DBH of 50-70 cm, the mass per tree could be approximately 20,000kg (20 t). With 10 trees/ha, the corresponding biomass would be about 200 t/ha. The below table summarizes this example.

Thus, the implications of large trees on biomass (and carbon) per ha is very significant. Although selective logging may only remove a few trees per ha (and damage surrounding ones), timber harvests can cause substantial decreases in total biomass and carbon stock.

Example of tree biomass composition in a hectare of tropical forest

DBH (cm)	Kg/tree	No. Trees / ha	Mass (t/ha)
10-19	135	900	121.5
20-29	2 250	70	157.5
30-49	8 500	20	170.0
50-70	20 000	10	200.0

Priority carbon pools for national accounting

15. The decision of which carbon pools should be measured as part of a national carbon accounting scheme are determined by several factors, such as:

- availability of financial resources,
- availability of good quality of existing data,
- ease and cost of measurement,
- the magnitude of potential changes in carbon pools.

16. In IPCC terminology, the prioritization of carbon pools process is regarded as "key category analysis." Major sources and sinks of CO_2 are identified at specific reporting levels: Tier 1 or global scale data for non-key categories (or lower priority categories) and Tier 2 and 3 or finer scale/resolution for key categories. (IPCC, 2006, Vol 4, Chapter 1.3.3)

17. Since carbon estimates at the national level could be incomplete and highly uncertain, a principle of ***conservativeness*** should be applied to increase credibility of the estimates (Grassi et al., 2008). Conservative analysis implies not overestimating, and/or minimizing the risk of overestimation and error propagation. For example, not including soil carbon in the accounting is a conservative approach. Although fewer REDD+ credits might be obtained as a result, the inclusion of soil carbon could decrease the credibility of the estimates of total emissions reductions. (For details of the application of this principle see Grassi et al., 2008.)

18. Given limited resources, fieldwork to estimate carbon stocks needs to be selective. The highest carbon pools with the greatest likelihood of conversion/emission should prioritized. (See Chapter 4 for more information on drivers of deforestation and degradation). For example, the more vulnerable forest areas to change tend to be those with higher opportunity costs, such as forests next to roads.

19. Table 5.1 summarizes priorities in measuring different carbon pools along with the methods and relative cost involved. In general, we suggest giving the highest priority to tree biomass and soil carbon. The carbon stock of field crops tends to be low and can be inferred from the literature. For peatlands, the highest carbon pool is the peat itself and thus measurement of its carbon content is highly recommended.[45]

[45] Nevertheless, it is not clear whether or how peatlands will be included in REDD+.

Table 5.2. Priorities and costs of measuring carbon by land use

C pool	*Method*	Land use					
		Forest		Perennial		Annual Crop	
		Cost	*Priority*	*Cost*	*Priority*	*Cost*	*Priority*
Tree biomass	*DBH and allometric equations*	2	4	2	4		
Understorey biomass	*Destructive samples*	4	2	4	1		
Crop	*Literature, secondary data*					2	3
Dead biomass	*Non destructive*	2	2	2	1		
Litter	*Destructive*	3	2	2	1		
Soil C	*Destructive: density and C content*	4	3	4	3	4	3

Note: Higher values indicate greater priority (shaded green) or higher cost (shaded red). Example from Indonesia.
Source: Authors.

Establish a carbon analysis framework

20. Clear and simple approaches to carbon stock measurement contribute to transparent national accounting. The simplified approach proposed here is for establishing a carbon basis for opportunity cost analysis. Although more straightforward, the approach is not always consistent with the detailed carbon calculation methods stipulated in the *Good Practice Guidance* (GPG) of the IPCC.[46] The GPG provides procedural information to classify, sample and collect data for national accounting of carbon stocks and greenhouse gas emissions and removals associated with Agriculture, Forestry and Other Land Use (AFOLU) activities. Generally, all data should be:

- ***Representative***: Capable of representing land-use systems/land cover categories, and conversions between land-use systems/land cover, as needed to estimate carbon stock changes and GHG emissions and removals;
- ***Time consistent***: Capable of representing land-use systems/land cover categories consistently over time, without being unduly affected by artificial discontinuities in time-series data;
- ***Complete***: All land within a country should be included, with increases in some areas balanced by decreases in others, recognizing

[46] Examples include: (1) the use of a 4:1 default value for the shoot/root ratio, (2) a carbon conversion factor of 0.46 for living biomass, necromass and soil organic matter.

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***: Data sources, definitions, methodologies and assumptions should be clearly described.

Two methods for carbon measurement

21. Changes in average carbon stocks per land cover can be monitored using various methods, including secondary datasets and estimations from the IPCC (2003b). In addition, countries can conduct *in situ* forest inventories and sampling using permanent plots for land-use systems. To measure changes in carbon stocks resulting from degradation, the IPCC (2006) recommends two non-mutually exclusive options (Figure 5.2):

- the stock-difference method, and
- the gain-loss method.

22. The ***stock-difference*** method uses carbon stock inventories from land uses to estimate sequestration or emissions. Carbon stocks in each carbon pool are estimated by measuring the standing stock of biomass at the beginning and at the end of the accounting period.

23. The ***gain-loss*** method is based on growth models with an ecological understanding of how forests and other land uses grow, along with information on natural processes and human actions that lead to carbon losses. Biomass gains are estimated on the basis of typical growth rates in terms of mean annual increment minus biomass losses estimated from activities such as timber harvesting, logging damage, fuelwood, and other products collection, overgrazing as well as from fire (Murdyarso, et al., 2008). The cost of this method is usually lower because carbon pools are determined only once in the beginning and then modeled over time.

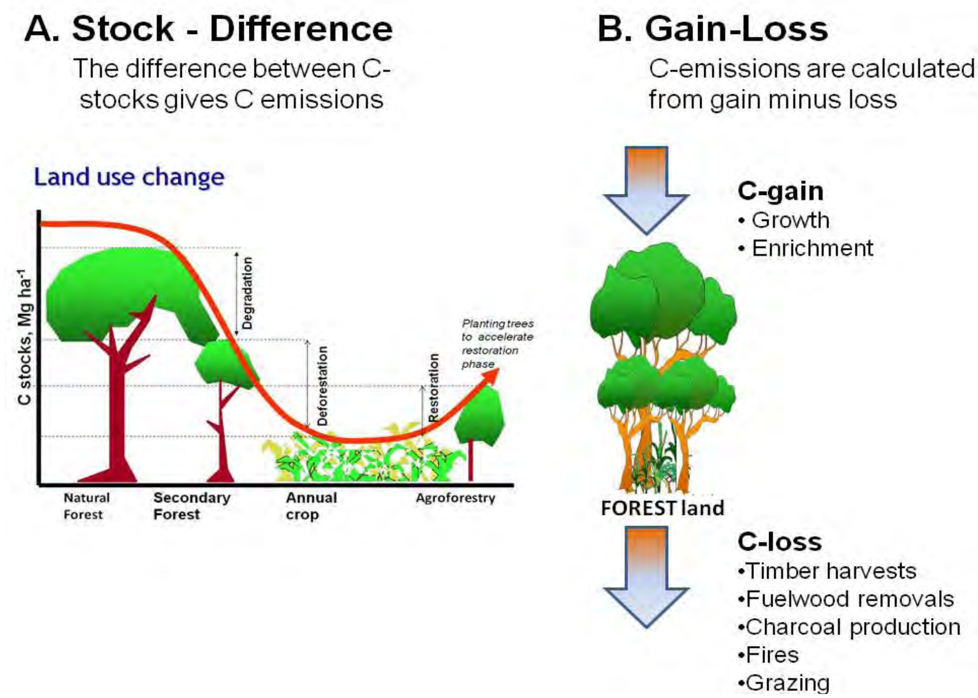


Figure 5.2. Comparison of stock-difference and gain-loss methods

Source: Modified from Murdyarso et al., 2008

24. The choice of measurement method will depend largely on the data availability, and on the resources and capacities to collect new data. If the purpose is national carbon accounting, a combination of both methods can be used. Consistency checks are needed, however, if methods are combined.

25. The measurement approach used in this training manual is the stock-difference method, because we need a single 'typical carbon stock' of a land use system (t C/ha), for comparison with a typical economic attribute (NPV) ($/ha) to calculate the ratio for any type of land use change.

Estimate "typical carbon stock" of a land use

26. For the purpose of a REDD+ opportunity cost analysis, a value of a typical carbon stock is needed for each land use (in IPCC, 2000, this was termed a **time-averaged carbon stock**). This single value is used for carbon accounting purposes and compared with a single-value profitability estimate of net present value (NPV). A typical carbon stock value integrates the gains and losses over a life-cycle of a land use. Below, we discuss (1) steps to establish a national carbon accounting system, (2) approaches for measuring carbon, and (3) assessment of carbon data quality, sampling procedures and field measurements of carbon stocks.

27. Determining the typical carbon stock starts by recognizing the life-cycle of the land use (see Figure 5.3). A 'time-averaged' carbon stock recognizes the dynamics of land uses

(Palm et al., 2005). This approach accounts for tree re-growth and harvesting, and allows the comparison of land uses that have different tree growth harvest rotation times and patterns.

28. For land uses that are in equilibrium 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 an estimate equals the sum of gains and losses of carbon. For land use systems that are increasing in area, the spatial average will be lower than the time-averaged value, and likewise the spatial average will be higher than the time-averaged value for systems that are in decline. Therefore, the carbon loss or sequestration potential of a land use system is ***not*** determined by the maximum carbon stock of the system at any one point of time, but rather by the average carbon stored in that land use system during its life-cycle (ASB, 1996). Specific steps to calculate time-averaged carbon stock for a monoculture and mixed systems are in **Appendix D**.

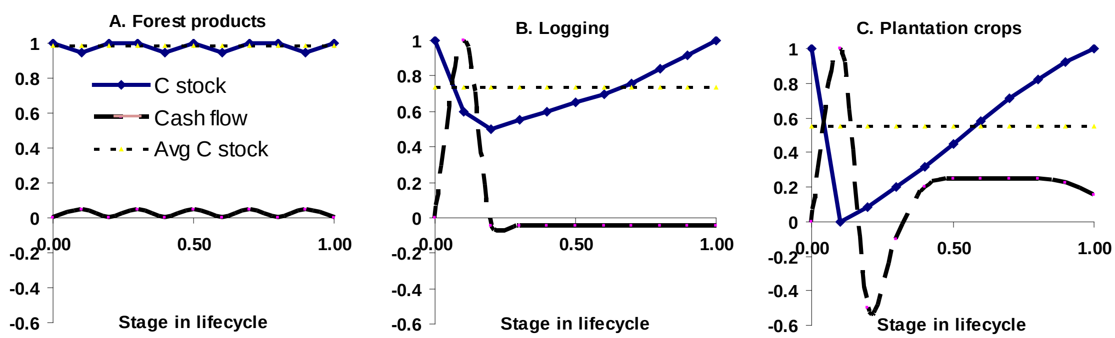


Figure 5.3. Aboveground carbon stock and cash flows of three land uses

´Time-averaged carbon stock´ in agroforestry systems

29. In agroforestry systems, where farmers incorporate various trees on farms, the carbon stocks behave differently than in cropland or managed forests. For example, trees in agroforestry systems are harvested more frequently than under forest management. To estimate carbon stocks, it is useful to develop annual time courses of the carbon stocks. In Figure 5.4, solid (darker) lines represent the annual carbon stocks, while dotted (lighter) lines depict corresponding time-averaged carbon stocks of: 230 tC/ha for forest, 80 tC/ha for agroforestry, and 29 tC/ha for annual crops or *imperata* grasslands of degrading productivity.

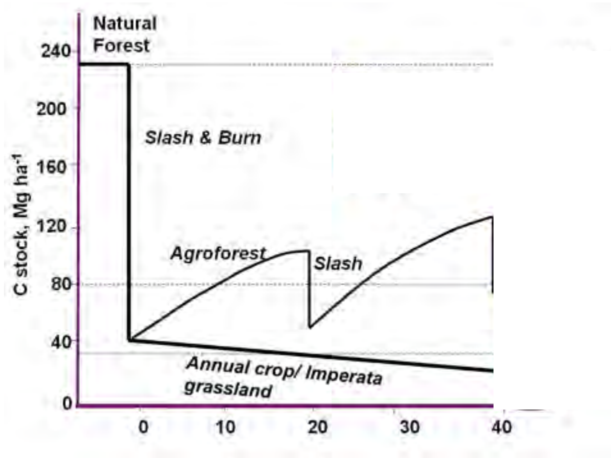


Figure 5.4. Example carbon stock changes of different land uses
Source: IPCC/LULUCF-section 4 (2000)

Accounting for forest degradation

30. Even without converting forests to other uses, carbon emissions can be produced from forest degradation. Forest degradation can be defined as *direct human-induced long-term loss (persisting for X years or more) of at least Y per cent of forest carbon stocks (and forest values) since time (T) and not qualifying as deforestation* (IPCC, 2003a). Despite this definition, agreement has not yet been reached on an operational procedure for monitoring, reporting and verification (MRV) of degradation. The measures of X, Y and minimum area are difficult to specify since the values depend on types of degradation activities and forest composition (Murdiyarso et al., 2008).

31. Common activities that degrade forests in the tropics include (GOFC-GOLD, 2009):

- Selective logging
- Large-scale and open forest fires
- Collection of fuelwood and non-timber forest products
- Production of charcoal, grazing, sub-canopy fires, shifting cultivation.

32. Apart from selective logging, few analyses has been made of the impacts of these processes on the loss of forest biomass and the time needed for regrowth. Estimating the carbon stocks of forests in contexts of deforestation and degradation requires monitoring of: (1) changes in forest area by forest type and (2) average carbon stocks per unit area and forest type (IPCC, 2003b). A Tier 1 analysis keeps track of area changes within forest categories and uses global default values for carbon densities of those forest categories. At Tier 2, precision and accuracy are increased by estimating carbon densities using country-specific data instead of global default values. A Tier 3 analysis uses models and inventory systems to adjust estimates to national circumstances repeatedly over time, thereby measuring changes in carbon densities within the accounting period.

Table 5.3. Measuring forest degradation: stock-difference and gain-loss methods

Activity	*Stock-difference method*	*Gain-loss method*
Selective logging	• Legal harvesting usually requires measurement of biomass after harvesting, thus necessary data should be available. • Illegal harvesting would require additional data collection. • Data on undisturbed forest can be used as a proxy if pre-harvesting data for particular sites is not available.	• Uses estimates of mean annual increment (MAI)and centralized records on timber extraction activities. • Reliability depends on honesty of timber companies in reporting rates of extraction.
Large-scale forest fires	• Reference data from undisturbed forest can be used for the pre-fire situation, but forest inventory would be needed to measure post-fire biomass.	• Losses due to fire can be estimated from the area burned and emission factors used to estimate the emissions based on the biomass lost.
Harvesting of fuelwood and non-timber forest products	• Pre-harvesting biomass levels could be estimated from typical levels in undisturbed forest, but in practice much of the forest subject to these uses will already be partially degraded at the start of the accounting period. • In areas already under individual or community management, pre- and post period forest inventories can be carried out by forest users.	• Data on losses (e.g., registers of commercial wood-based products, estimates of fuel wood use) may be available. • Fuel wood off-take could also be calculated using population and data on average household fuel wood consumption. • Data on gain available from standard MAI statistics.
Cattle grazing, shifting cultivation, sub-canopy fire	• Pre-harvesting biomass levels could be estimated from typical levels in undisturbed forest, but most forests subject to these changes will already be partially degraded at the start of the accounting period. • Community measurements can be made and can help establish local 'ownership' of the process.	• Data on gain are available from standard MAI statistics. • Data of losses are rarely available in national statistics.

Source: Murdiyarso, et al. 2008.

Diagnosing existing carbon data

33. When compiling or reviewing estimates for the typical carbon stocks of land uses, a variety of data may already be available. Such information can be categorized according to IPCC tier:

- *Tier 1:* Global scale data (remote sensing imagery).
- *Tier 2:* National scale data
  - forest inventory data, often focused on timber volumes of commercially-attractive timber species, yet potentially including all trees,
  - Primary data that can be converted to total biomass estimates,
- *Tier 3:* Plot/watershed data

- bio-economic models of biomass production under different management regimes, calibrated on plot-level biomass data (usually available for main crops and some plantation crops),
- ecological data on long-term plots that include all biomass and necromass pools.

34. As mentioned earlier, the prioritization of carbon pools or "key category analysis" takes into account the major sources and sinks of carbon and associated reporting level. Non-key categories, or lower priority categories, can be reported with Tier 1 data whereas key categories should use Tier 2 and 3 or finer scale/resolution data (IPCC, 2006, Vol. 4, Chapter 1.3.3). Existing carbon data within a country may be of varying types and quality. Therefore, a diagnosis of available national carbon data is needed to identify gaps and areas of weakness, where new data collection is warranted.

35. Since virtually all types of remote sensing depend on ground-based carbon stock measurements, efforts to spatially extrapolate and analyze temporal changes require carbon data sampled using transparent protocols. With any such data their usefulness and value depend on:

- adequate description of the method used in selecting the plots,
- completeness of records that allow the plot to be interpreted as part of a land use system with known intensity and time frame,
- representativeness of the collection of plots for the domain to be represented (e.g., across climatic, soil, and accessibility variations),
- adequate description of the method used in measurement, including the sample size or sampling intensity used in 'plot-less' sampling ,
- viability of the primary data and opportunity for further calculations.

36. Questions regarding any of these issues can make data suspect for use, and may at the least warrant a sampling program to fill gaps and check uncertain parts of the data set.

Measuring carbon of different land uses

37. A basic premise of the IPCC *Good Practice Guidance* (GPG) is that land can be allocated to one (and only one) of six categories described below. A land use may be considered a top-level category for representing all similar land-uses, with sub-categories describing special circumstances significant to carbon content, and where data are available.[47]

38. This IPCC GPG assumption of non-ambiguous land categories may agree with existing institutional traditions in some countries, but the premise can create challenges. Where does a rubber agroforest on peatland belong? Such a land use (1) meets the minimum tree height and crown cover of forest, but is (2) on a wetland, and (3) its production is recorded

[47] For REDD+ opportunity cost analysis, sub-categories are also needed for land use systems generating different levels of profit.

within agricultural statistics. Therefore, consistency of accounting methods across land categories requires a good understanding of such relations. The IPCC land categories are:

(i) Forestland

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

(ii) Cropland

40. This category includes agricultural land, including rice fields, and agroforestry systems where the vegetation structure (current or potentially) falls below the thresholds used for the *Forestland* category.

(iii) Grassland

41. 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 brushes that fall below the threshold values used in the *Forestland* category. The category also includes all grassland from wild lands to recreational areas as well as agricultural and silvopastoral systems, consistent with national definitions.

(iv) Wetlands

42. This category includes areas of peat extraction and land that is covered or saturated by water for all or part of the year (e.g., peatlands) and that does not fall into the *Forestland*, *Cropland*, *Grassland,* or *Settlements* categories. It includes reservoirs as a managed sub-division and natural rivers and lakes as unmanaged sub-divisions.

(v) Settlements

43. 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

44. 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 (e.g., 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.

Box 5.2. Off-site carbon storage

Part of the biomass of forests, tree crop plantations, or annual cropping is removed from the field and enters within economic trade flows. Although efforts have been made to assign the carbon stocks of such products to the areas where they originated (especially in the case of wood), the integrity and transparency of the global carbon accounting system would be at risk if such calculations were to be made.

Current IPCC (2006) guidelines do not include off-site products as part of the system, although stock changes in the forest can be estimated from the difference between biomass increment and offtake (e.g., removals, harvests), if there are reliable data for both. Carbon stock accounting benefits from the simplicity that at any point in time all stocks can be inspected on site.

C stock sampling and measurement

45. Once the carbon pools to be measured are prioritized and the measurement method is defined, sampling will follow a series of guidelines with respect to the:

- sampling scheme, including stratification (See Chapter 4 of this manual, Dewi and Ekadinata, 2008, and Winrock, 2008)
- hierarchical system for land use classification (see Chapter 4).

46. Guidelines for obtaining the number of samples units needed can be found in Box 5.4. It is important to note that increasing the desired level of accuracy and precision will have cost implications.

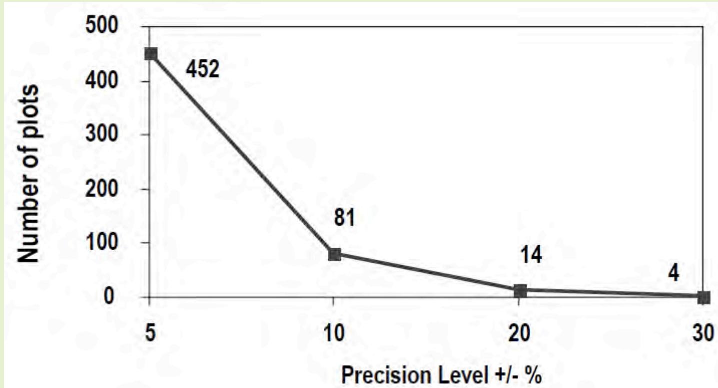
Box 5.3. Steps to determine the number of sampling plots

Step 1. Select the desired level of accuracy and precision

The selection of precision and accuracy level 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 Clean Development Mechanism (CDM) forestry projects can use a precision level up +/- 20% (Emmer, 2007). Nevertheless, specific levels of precision can be defined for each type of land use system of the inventory. The highest precision generates higher costs.

The following figure illustrates the relationship between the number of plots and the level (degree) of precision (+/- % of total carbon stock in living and dead biomass) with 95% confidence for four types of combined carbon pools (above- and below-ground biomass, litter and soil organic matter) present in six vegetation categories of the Noel Kempff project in the tropical forest of Bolivia.

To achieve a precision level of +/-5%, 452 plots are needed, whereas only 81 plots would give a +/-10% level of precision. This example illustrates the cost-benefit implications of a higher precision level.



Source: IPCC 2003b, Chapter 4-3.

Step 2. Select areas for making preliminary data gathering

Before determining the number of plots required for monitoring and measurement carbon, an estimate of the existing variance must be obtained for each type of deposit (e.g. soil carbon) in each land use system corresponding to 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, a recommended set is four to eight repetitions for each land use system.

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

The time-averaged carbon stock is calculated of each land use system or land use legend from the preliminary data (or obtained from literature if one can find studies of similar area).

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* *Std. deviation*

Step 4. Calculating the required number of sampling plots

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

Formula 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 x level selected).
As seen in the previous step, the recommended level of accuracy is ± 10% (0.1) of average but be up to ± 20% (0.2).
t = statistical sample of the t distribution for a 95% level of confidence (usually used as a sample number)
N = number of plots in the area of the layer (stratum area divided by the plot size in ha)
s = standard deviation of land use system

Source: Section adapted from Rugnitz, et al., 2009.

Online tools for calculating number of plots: Winrock International has developed an online tool: "Winrock Terrestrial Sampling Calculator" that helps calculate the number of samples and estimating the costs for base line studies as well as monitoring.
See: http://www.winrock.org/ecosystems/tools.asp

47. Once the number of sampling units is calculated, a design of the sample is needed. Figure 5.6 summarizes the recommended sizes of plot and sub-plots under each sampling unit.

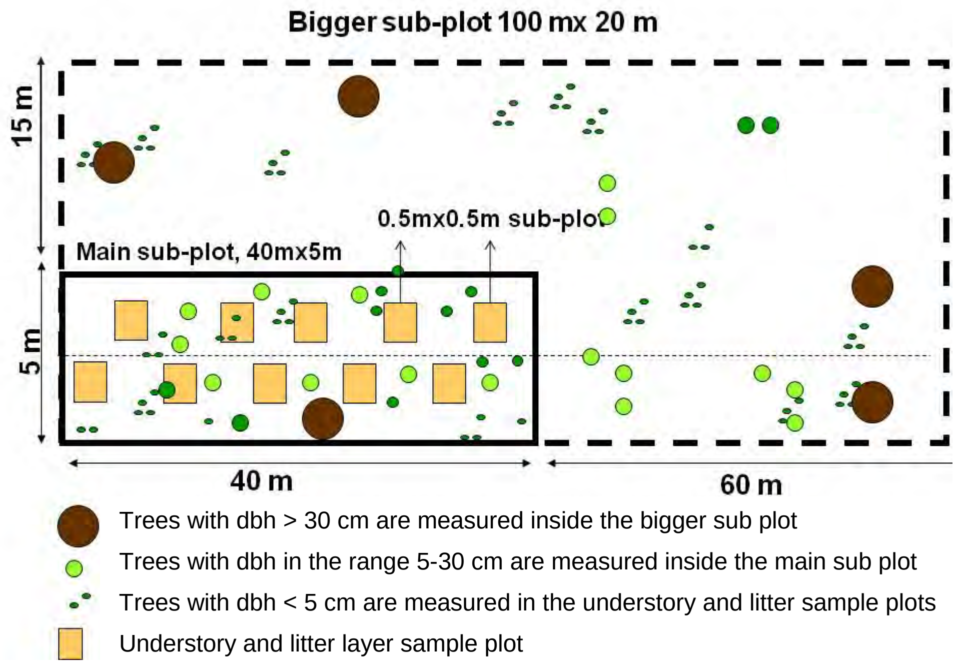


Figure 5.5. Recommended plot and sub-plots sizes for carbon stocks sampling

Source: Hairiah, et al. 2010.

Plot level sampling

Measuring carbon stock at the plot level requires assessing:

- Biomass
  - o destructive sampling of small plots of understory vegetation, annual crops, or grasses, and
  - o non-destructive tree biomass estimates using allometric biomass equations.
  - o default values for below-ground biomass (roots).
- Necromass
  - o destructive (for litter remains on soil surface) or
  - o non-destructive (for dead wood).
- Soil organic matter.

48. The procedures of carbon measurement of various pools are explained in detail in Hairiah, et al., 2010 (in English), Rugnitz, et al., 2009 (in Spanish and Portuguese) and several additional resources are available from GOFC-GOLD (2009).

49. The most important carbon stock pool is tree biomass. To calculate carbon stocks in trees we need to know:

- total number of trees per ha,
- distribution of their diameter at breast height,
- two parameters that relate biomass to stem diameter ('allometrics').

50. The devil is in the details. It is necessary to both (1) use the correct allometric equations (and to know when not to use the standard ones), and (2) to know the diameter frequencies, especially those for big trees. Using allometric equations from the literature can simplify the carbon stock calculations at the landscape level. Guidelines for choosing the right allometric equation(s) should be followed (Chave, et al. 2005; see Table 5.3 for a description of the criteria). If any of the criteria are ***not*** met, it is recommended to develop local allometric equations. If there are several equations that meet the criteria, choose the one with highest value for R^2 (for a detailed procedure see Rugnitz et al., 2009, p.51-59). A list of allometric equations by species and type of forest is shown in **Appendix C**.

Table 5.4. Criteria for choosing an allometric equation

Criteria	Description
Soil and climate conditions	Similar climatic conditions within the sample area to that of where the equation was developed for: - Annual mean temperature - Annual precipitation - Altitude Wherever possible, similar soil conditions.
Harvested species	At least 30% are of forest species used in the equation are present in the sample area
Tree sizes	Similar diameter at breast height (DBH) and tree height

Source: Adapted from Rugnitz, et al., 2009.

Box 5.4. Large trees, large roots... but not always

Large trees tend to have large roots. For mixed tropical forests, the ratio of above to below-ground biomass is approximately 4:1. In very wet conditions, the ratio can shift upwards to 10:1; 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). As measurement of root biomass is not simple (although there is a method that uses the root diameter at stem base and allometric equations), we normally use default assumptions for the shoot:root ratio based on available literature (Cairns et al., 1997; Mokany et al., 2006).

From plot to land use

51. For calculating carbon stock changes at the landscape level, we need data of the typical carbon stock or time-averaged carbon stock of each land use - ***not*** the carbon stock of each plot under current conditions. Here, we refer to the spreadsheet provided with this manual. The spreadsheet **OppCost** in the file **SpreadsheetexercisesREDDplusOppCosts.xlsm** links the carbon stocks for land use change according to land use category. A couple of examples to calculate time-average carbon stock for monoculture and diverse systems are

shown in **Appendix D**. Estimated values of time-averaged carbon stock of selected land-use systems from various countries are shown in Table 5.4 below.

Table 5.5. Time-averaged carbon stock (mean and range) of selected land uses

Land use	Time averaged carbon stock, Mg /ha	Reference, remarks
Primary forest (Indonesia)	300 (207-405)	Palm et al., 1999
Selectively logged forest (Central Kalimantan, Indonesia)	132	Brearly et al., 2004
Shrub/crop rotation	15	Prasetyo et al. (2000)
Imperata grassland	2	Palm et al. (2004)
Oil palm (Indonesia)	60	Recalculated from Rogi (2002)
Oil palm (Indonesia)	40	Recent data ICRAF-Indonesia
Rubber agroforest, 25 year old (Sumatra, Indonesia)	68	Averaged from Palm et al. (2004)
Rubber agroforest, 40 year old (East Kalimantan, Indonesia)	100	Rahayu et al., 2004
Coconut plantation	60	Adjusted from 98 Mg ha^{-1} according to IPCC (2006) based on Rogi (2002)
Jatropha plantation	10	June (2008) based on Niklas (1994)
Tea plantation	28	Adapted from Kamau et al. (2008)
Sugar cane	9	Soejono 2004, modified
Coffee-based agroforestry system	51	Hairiah (2007, for shaded coffee)
Cacao	58	Lasco et al. (2002)

From land use to sub-national region

52. Once the time-averaged carbon stock per land use system is obtained, we need to calculate/estimate the time-averaged carbon by land cover in order to extrapolate to landscape level. For example, in Figure 5.6, the “Plantation” land cover comprises five different land uses (pinus, agathy, mahogany, clove, and bamboo). Because it is not possible to distinguish these land uses at the land cover level (and the time-averaged carbon stock has relative small variation/deviation), an average for the land cover is estimated.

53. Once the time-averaged carbon stocks per land cover have been estimated, use them to extrapolate by multiplying by the area in the landscape of analysis in year y using the results of a GIS analysis. Then repeat the procedure in the map of year y+10, and then calculate the difference in carbon stocks.

Land cover	LUS	Plant density per ha	Total C stock, Mg ha^{-1}	Max. Age, year	Time Avg. C Stock, Mg ha^{-1}	
1.Forest	Degraded Forest	2248	161	50	161	161
2. Agroforestry	AF_Multistrata	3970	123	30	111	111
	AF_Simple	4018	99	30		
3. Plantation	Pinus	795	183	30	144	
	Agathis		190	40	146	
	Mahogany	963	198	50	212	139
	Clove		142	35	70	
	Bamboo	3188	159	15	121	
4. Grassland	Napier grass, 4 months	-	100	0.25	11	11
	Napier grass, 1 month	-	78			
5. Annual crop	Vegetables	-	79	0.25	1.5	1.5

Pennisetum purpureum (Rumput Gajah=napier grass)

Figure 5.6. Extrapolating carbon from land uses to land covers at the landscape level

Source: Hairiah, et al, 2010.

From sub-national region to nation

54. Scaling-up landscape carbon estimates to sub-national and national levels requires a combined effort of different government agencies, NGOs, and other institutions. At the national level, the data available normally corresponds to land cover level. The availability of specific spatial national data sets varies from country to country and the information is often scattered among different Ministries (Agriculture, Fisheries, Environment, Mining and Energy) or specialized government agencies.

55. Within countries, different areas with similar conditions have often been identified already with respect to climatic, elevation or vegetation. These different classes should be used as the basis for the stratification process within sampling scheme (Box 5.4) and the development of a land use map. Such information may likely be sufficient to spatially differentiate areas of similar carbon content, especially within forests. However, some weaknesses of the approach derive from:

- errors in classification of the pixels into land cover classes,
- uncertainty on the average carbon stock values per class,
- changes in carbon over time.

56. Inaccuracy and uncertainty of forest inventory data can range up to a multibillion-ton difference in the global stock of carbon in trees. Sources of error include area of forest, timber volume per area, biomass per timber volume, and carbon concentration. Since the factors are multiplied together to estimate carbon stock, a more precise measurement of the most certain variable improves accuracy little. In contrast, a 10% error in biomass per

hectare, for example, can cause a discrepancy equivalent to a mistake of measuring forest area by millions of hectares. Thus, unbiased sampling of regional forests is of important to accurately monitoring of global forests (Waggoner, 2009).

57. From the perspective of an opportunity cost analysis, the land use categories are key to identify and quantify the different land uses at the landscape and national level. Each land use should have a corresponding carbon content. By comparing and calculating the differences between carbon content of the different land uses in year y and year y+5, y+10 or the intervals defined, it would be possible to estimate the change in carbon stocks. Nevertheless, either using Tier 2 or Tier 3 data, weaknesses of the approach derive from:

- Errors in spatial classification by land use types, combining 'land cover phases' with on-the-ground characteristics and management styles,
- Uncertainty on shifts in time-averaged carbon stocks within the land use categories.

Building a national monitoring system

58. The UNFCCC (2009) has identified key elements and capacities for building national carbon monitoring systems for REDD+ as well as components and required capacities for establishing a national monitoring system for estimating emissions and removals from forests. These key elements include:

- Being part of a national REDD+ implementation strategy or plan,
- Systematic and repeated measurements of all relevant forest-related carbon stock changes,
- The estimation and reporting of carbon emissions and removals at the national level that either use or are in line with the methodologies contained in the IPCC good practice guidance for LULUCF due to the need for transparency, consistency, comparability, completeness, and accuracy that should characterize such systems.

59. The key components and required capacities for establishing a national monitoring system for estimating emissions and removals from forests are explained in detailed in UNFCCC, 2009, pages 8-10 and include:

- planning and design,
- data collection and monitoring,
- data analysis,
- reference emission levels, and
- reporting.

60. **Appendix B** provides a summary table of required capacities for a national monitoring system of emissions.

61. At a finer scale, the challenges about data collection (Tier 3) equally refer to data collected by 'forest professionals' and community members. Quality control measures that

identify outliers and unexpected results need to be in place for whoever collects the primary data. Unexpected results may indicate an opportunity to learn, if they are confirmed via cross-checking. Nevertheless, inaccurate “participatory” results may skew overall results if retained in the dataset.

A forest carbon database

62. Carbon data is becoming more available. A Forest Carbon Database and exchange system is being developed within the public domain (CIFOR, 2010; Kurnianto and Murdiyarso, 2010). The database helps national and sub-national monitoring, reporting and verification of REDD+ activities. The open access database is designed to allow participation of researchers and practitioners, who conduct regular forest inventory, manage sample plots, and conduct research on forest carbon stocks and related topics.

63. The system allows the accounting of the five carbon pools. Supporting information can also be added (e.g., site details, land cover, climate and soil) to share the context of the carbon stock data. If the entire inventory of data is uploaded, the carbon stock will be automatically calculated, per factor that recognize ecosystem factor (e.g., rainfall, temperature). The system:

- reduces duplicate data collection by making data available, which have already been collected. This reduces costs.
- provides easy access to data that cannot be readily replicated, such as large surveys that are too expensive to replicate.
- enables comparison carbon stocks across land use types based on data provided by other contributors.

Cost estimates of measuring carbon and capacity building

64. Building a national or sub-national carbon stock inventory is a time-consuming and costly exercise. Although many countries are familiar with conducting forest inventories, carbon accounting is a step further. Carbon accounting outside forests or in mixed land use systems also increases the complexity of this task. Therefore, one of the initial major costs of measuring carbon faced by some countries is developing professional capacity.

65. Given the high and changing carbon content of forests and possibility for inaccurate measures, many efforts are advancing to improve cost effectiveness of ground-based inventories and surveys. Stratification of forests by carbon stock (e.g. affected by timber harvest), not necessarily by forest type, can reduce uncertainty and costs (Brown, 2008)

66. In the short term, capacity building is desirable at the national/sub-national level. In the medium to long term, some cost-effective approaches can be applied, such as: building institutional alliances, involving communities, and introducing specific carbon measurement topics and field practices in [tertiary] education curricula, and mainly, using

available national skills. In some cases, foresters, biologists, ecologists, etc., can transfer some of the basic skills for carbon measurement to communities living in the forest and forests margins. Such an approach encourages local community participation and reduces the costs in the long term.

67. Table 5.5 summarizes relative costs of using data of different resolution, capacities to be used and required capacities. Although the involvement of international organizations also results in higher costs, skills can be transferred to national and local levels through partnerships and alliances to achieve cost savings. Start-up costs are usually higher than maintaining and upgrading the capacities.

68. Costs will differ according to the country and extent of data gaps. Below are estimated costs for equipment and personnel for above-ground biomass sampling in Colombia (Table 5.6) and a national forest inventory in India (Table 5.7). The average cost of assessing forest cover and changes on a per unit area basis in India is US$ 0.60 per km^2. The cost per unit is derived from the total forest cover of the country, which is estimated at 677,088 km^2.

Table 5.6. Relative costs of building a national carbon accounting inventory

Issue	**Scale**		
Data resolution	**Tier 1: Global estimates**	**Tier 2: National available data**	**Tier 3: Plot/watershed data**
	Freely available online but need expert knowledge to interpret data	Not freely available and scattered in most cases. Costs are mostly related to the bureaucracy to obtain the data	Normally only available at small scale or very specific and not freely available or need to collect own data. Sources are local or regional institutions or government
Relative cost	$	$$	$$$
Capacities used	**International expertise**	**National expertise**	**Local expertise**
	Personnel from international organizations (WB, UN, NGOs, etc) with direct access to governments and normally involved in the start-up of the process	Personnel from national government agencies and local NGOs, education institutions, usually based in the cities and setting national standards/policies	Local experts (e.g., universities and communities based in tropical forests). Some have built alliances with international experts or other national experts
Relative costs	$$$$	$$	$-$$
Capacities required for MRV	**Start-up**	**Maintain**	**Upgrade**
	Initial set up, varies according to current in country capacity	Keeping up to date and implement quality assurance and quality control schemes	Specialized training, participation in international conferences or access to international standards
Relative costs	$$$	$$	$$-$$$

Source: Authors.

Table 5.7. Equipment and personnel for above ground biomass sampling in Colombia

Activity	Equipment	Personnel	Time (*per plot, **per tree)
Sampling non-tree vegetation	1 GPS 5 m nylon cord 3 machetes 1 25 kg or more scale 1 scale of 1 to 5 kg with 0.1 g accuracy Plastic bags, markers, pencil, forms	3 people	40 - 60 minutes*
Forest inventory	1 GPS 1 50 meter tape 1 hypsometer 3 machetes 1 2m long wood pole (can be obtained in the field) 30 m nylon cord Markers, pencil, forms	3 people	120-150 minutes*
Trees and palms	1 chain saw 1 metallic tape 4 machetes 1 scale 50 kg or more 1 scale 1 to 5 kg capacity and 0,1 g accuracy Plastic bags, Markers, pencil, forms	4 people	1-5 hours**

* Number of plots sampled in a day will depend on the transport time within sample points.
** Time varies according to the size (and hardness) of the tree.
Source: Carbono y Bosques, 2005, cited in Rugnitz, et al. 2009.

Table 5.8. Cost of measuring forest cover and change using satellite imagery in India

Components	Cost per 100 km² (US$)	%
Human resources (cost of data interpretation by technicians, supervision and checking by professionals and ground truthing)	38.5	64
Cost of satellite data (IRS.P6- LISS III of 23.5 x 23.5 m)*	6.5	11
Equipment (cost of hardware/software with assumed life of 5 years plus day-to-day maintenance, air conditioning plant, network, etc.)	15.0	25
Total	*60.0*	*100*

*Exchange rate used is 1 US$ = 50 Indian Rupees. In total, 393 satellite scenes using IRS P-6 LISS III cover the entire country. The area of each scene is about 20,000 km^2.
Source: UNFCCC, 2009.

Measurement priorities arising from forest condition

69. The cost of measuring and monitoring degradation depends on national circumstances, which include factors such as the:

- area of forest cover
- forest stratification (e.g., Democratic Republic of Congo has one major forest type, whereas Indonesia and Mexico have four or more)
- Tier level of carbon accounting

References and further reading

Achard, F, Eva HD, Stibig H-J and Mayaux P, Gallego J, Richards T and Malingreau J-P, 2002. Determination of deforestation rates of the world's human tropical forests. *Science* 297: 999-1002.

Agus, F., I.G.M. Subiksa, 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. 36p.

Agus F, Runtunuwu E, June T, Susanti E, Komara H, Las I, van Noordwijk M. 2009. Carbon budget in land use transitions to plantation. *Indonesian Journal of Agricultural Research and Development* (In Press).

Angelsen, A. 2007. *Forest cover change in space and time: combining von Thünen and the forest transition.* World Bank Policy Research Working Paper. WPS 4117. World Bank, Washington D.C.

Brearly, F. Q., Prajadinata, S., Kidd, P. S., Proctor, J. dan Suriantata. 2004. Structure and Floristics of an old secondary rainforests in Central Kalimantan, Indonesia and a comparison with adjacent primary forest. *Forest Ecology and Management*, 195: 385-397.

Brown, S. 1997. *Estimating Biomass and Biomass Change of Tropical Forests: a Primer.* FAO Forestry Paper 134. FAO: Rome.
http://www.fao.org/docrep/w4095e/w4095e00.htm#Contents

Brown, S. 2008. *Assessment of the Advantages and Limitations of Ground-Based Surveys and Inventories.* UNFCCC Workshop on Methodological Issues Relating to REDD in Developing Countries 25-27 June. Tokyo, Japan.
http://unfccc.int/files/methods_and_science/lulucf/application/pdf/080625_tokyo_brown.pdf

Cairns M A, Brown S, Helmer E H and Bumgardner G A,1997. Root biomass allocation in the world's upland forests. *Oecologia*, 111: 1-11.

Chave, J., C. Andalo, S. Brown, M.A. Cairns, J.Q. Chambers, D. Eamus, H. Fölster, F. Fromard, N. Higuchi, T. Kira, J.P. Lescure, B.W. Nelson, H. Ogawa, H.Puig, B. Riéra, T. Yamakura. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia.* 145(1):87-99.

CIFOR, 2010. CarboFor: CIFOR's Carbon Forestry website.
http://www.cifor.cgiar.org/carbofor/

Couwenberg J., Dommain R. & H. Joosten (2009). Greenhouse gas fluxes from tropical peatlands in Southeast Asia. *Global Change Biology*, 16: 1715-1732.

Dewi, S. , Ekadinata, A., 2008. *Ground-truthing protocol.* Landscape Mosaics. CIFOR-ICRAF Biodiversity Platform.

Emmer, I. 2007. Manual de contabilidad de carbono y diseño de proyectos. Proyecto Encofor. Quito, Ecuador. 22p www.joanneum.at/encofor

Environmental Protection Agency (EPA), 2010. *Carbon sequestration in agriculture and forestry*. Available online at: http://www.epa.gov/sequestration/science.html (Last updated 26 June 2010)

Germer, J., and J. Sauerborn. 2008. Estimation of the impact of oilpalm plantation establishment on greenhouse gas balance. *Environmental Development and Sustainability* 10:697-716.

Gibbs, H.K., Brown, S., Niles J.O. and Foley J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD+ a reality. *Environ. Res. Lett*. 2 045023 (13pp).

GOFC-GOLD. 2009. *Reducing greenhouse gas emissions from deforestation and degradation in developing countries: A sourcebook of methods and procedures for monitoring, measuring and reporting, GOFC-GOLD Report version COP14*-2, (GOFC-GOLD Project Office, Natural Resources Canada, Alberta, Canada).

Grassi, G. S. Monni, S. Federici, F. Achard, D. Mollicone. 2008. *Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates*. Environ. Res. Lett. 3 (2008) 035005 (12pp) doi:10.1088/1748-9326/3/3/035005

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

Hairiah K, Dewi S, Agus F, van Noordwijk M, Rahayu S, Velarde SJ. 2010. *Measuring Carbon Stocks Across Land Use Systems: A Manual*. Bogor, Indonesia. World Agroforestry Centre (ICRAF), SEA Regional Office, Brawijaya University and ICALRRD (Indonesian Center for Agricultural Land Resources Research and Development) at www.worldagroforestrycentre.or/sea.

Houghton R A, Lawrence KT, Hackler JL and Brown S, 2001. The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. *Glob.Change Biol.* 7:731-746.

IPCC. 1997. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories – Workbook (Volume 2).* http://www.ipcc.ch

IPCC. 2000. *Land Use, Land-Use Change and Forestry. A Special Report of the IPCC.* Cambridge University Press, Cambridge, UK. 377pp.

IPCC. 2003a. *Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and devegetation of other vegetation types.* In: Penman, J., Gytarsky, M., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F. (eds.) IPCC-IGES, Kanagawa. Japan.

IPCC. 2003b. *Good Practice Guidance for Land-Use, Land-Use Change and Forestry*. In: Penman, J., Gytarsky, M., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner F. (eds.) IPCC-IGES, Kanagawa. Japan.

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.

Jaenicke, J., J.O. Rieley, C. Mott, P. Kimman, F. Siegert (2008). Determination of the amount of carbon stored in Indonesian peatlands. *Geoderma* 147: 151–158

Jauhiainen, J, Vasander H, Jaya A, Takashi I, Heikkinen J, Martikinen P. 2004. Carbon balance in managed tropical peat in Central Kalimantan, Indonesia. In: W*ise Use of Peatlands*, Proceedings of the 12th International Peat Congress, 6-11 June, 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.

June, T., Wahyudi A, Runtunuwu E, Syahbuddin H, Sugiarto Y, Hastuti S, Wihendar TN, Nugroho WT. 2008. *Potensi Serapan Karbon Jarak Pagar (Jatropha curcas, L) untuk Pengembangan Clean Development Mechanisme (CDM) Tanaman Perkebunan*. Laporan Tengah Tahun KKP3T. Institut Pertanian Bogor. Bogor. 16 p.

Kamau, D. M., J. H. J. Spiertz and O. Oenema. 2008. Carbon and nutrient stocks of tea plantations differing in age, genotype and plant population density. *Plant Soil* 307:29–39

Kurnianto, S. and Murdiyarso, D. 2010 *Forest carbon database: a Web-based carbon stock data repository and exchange system.* CIFOR, Bogor, Indonesia. 16p.

Lasco, R. D. 2002. Forests carbon budgets in Southeast Asia following harvesting and land cover change. *Science in China* (series C), Vol. 45 : 55-64.

Locatelli, B. 2007. Carbon pools slide. MSc course SA 507, CATIE.

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

Melling L, Hatano R, Goh KJ. 2005. Soil CO2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia, *Tellus* (2005), 57B, 1–11.

Mokany K, Raison J R, and Prokushkin AS, 2006. Critical analysis of root-shoot ratios in terrestrial biomes. *Global Change Biolology* 12: 84-96.

Murdiyarso, D., M. Skutsch, M. Guariguata, M. Kanninen, C. Luttrell, P. Verweij, O. Stella. 2008. Measuring and monitoring forest degradation for REDD: Implications of country circumstances. CIFOR Infobrief. No.16, November. http://www.cifor.cgiar.org/publications/pdf_files/Infobrief/016-infobrief.pdf

Niklas, K.J., 1994. *Plant Allometry, the Scaling of Form and Process.* University of Chicago Press, Chicago, 365 pp.

Palm, C., T. Tomich, M. van Noordwijk, S. Vosti, J. Gockowski, J. Alegre and L. Verchot. 2004. Mitigating GHG emissions in the humid tropics: Case studies from the Alternatives to Slash-and-Burn Program (ASB). *Environment, Development and Sustainability* 6: 145–162.

Palm, C.A., M. van Noordwijk, P.L. Woomer, J. Alegre, L. Arevalo, C. Castilla, D.G. Cordeiro, B. Feigl, K. Hairiah, J. Koto Same, A. Mendes, A. Moukam, D. Murdyarso, R. Nyomgamg, W.J. Parton, A. Ricse, V. Rodrigues, S.M. Sitompul, 2005. Carbon losses and sequestration with land use change in the humid tropics. *In*: C.A. Palm, S. Vosti, P.A. Sanchez and P.J. Ericsen (eds.) *Slash- and -Burn Agriculture, the search for alternatives.* p. 41-62.

Pearson, T., S. Walker, S. Brown, 2005. *Sourcebook for Land Use, Land-Use Change and Forestry Projects*. Winrock International.

Prasetyo, L. B., G. Saito, H. Tsuruta. 2000. *Development of database for ecosystem changes and emissions changes of GHG using remote sensing and GIS in Sumatera Island, Indonesia* http://www.gisdevelopment.net/acrs/2000/ts11/glc002pf.htm

Ramankutty N, Gibbs H K, Achard F, DeFries R, Foley J A, Houghton RA, 2007. *Glob.Change Biol.* 13:51-66

Rogi, J. E. X., 2002. *Penyusunan model simulasi dinamika nitrogen pertanaman kelapa sawit (Elaeis guineensis, Jacq.) di unit Usaha Bekri Propinsi Lampung*. Dissertation. Bogor Agricultural University).

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

Tomich, T.P., M. Van Noordwijk, S Budidarsono, A. Gillison, T. Kusumanto, D. Mudiyarso, F. Stolle and A.M. Fagi, 1998. *Alternatives to Slash-and-Burn in Indonesia. Summary Report & Synthesis of Phase II.* ASB-Indonesia and ICRAF-S.E. Asia.

UNFCCC, 2009. *Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks*. Technical paper (FCCC/TP/2009/1). Online.

van Noordwijk M., G. Lawson, A. Soumaré, J.J.R. Groot, K. Hairiah. 1996. Root distribution of trees and crops: Competition and/or complementary. In: Chin Ong and Peter Huxley (eds.) *Tree-Crop interactions - a physiological approach.* CABI - ICRAF. p 319-364.

Verchot, L. V., M. van Noordwijk, S. Kandji, T.P. Tomich, C. Ong, A. Albrecht, J. Mackensen, C. Bantilan, K. V. Anupama, C. Palm, 2007. Climate change: linking adaptation and mitigation through agroforestry. *Mitig Adapt Strat Glob Change.*

Waggoner, P. 2009. Forest Inventories: Discrepancies and Uncertainties. Discussion Paper RFF DP 09-29. Resources for the Future. Washington, D.C.

Winrock International, 2008. *Winrock Terrestrial Sampling Calculator.* Online spreadsheet. Available at: http://www.winrock.org/ecosystems/tools.asp

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