SOURCEBOOK

COP 18 version 1

A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation

GOFC-GOLD

Global Observation of Forest and Land Cover Dynamics

2.3 ESTIMATION OF FOREST CARBON STOCKS

Tim Pearson, Winrock International, USA

Nancy Harris, Winrock International, USA

David Shoch, The Nature Conservancy, USA

Sandra Brown, Winrock International, USA

2.3.1 Scope of section

> **Section 2.3 presents guidance on the estimation of the biomass carbon stocks of the forests being deforested and degraded. Guidance is provided on: (i) which of the three IPCC Tiers should be used, (ii) potential methods for the stratification by Carbon Stock of a country's forests and (iii) actual Estimation of Carbon Stocks of Forests Undergoing Change.**

Monitoring the location and areal extent of change in forest cover represents only one of two components involved in assessing emissions and removals from REDD+ related activities. The other component is the emission factors—that is, the changes in carbon stocks of the forests undergoing change that are combined with the activity data for estimating the emissions. The focus in this section will be on estimating carbon stocks of existing forests that are subject to deforestation and degradation. Although little attention is given here to areas undergoing afforestation and reforestation, the guidance provided is applicable. Further guidance for forestation is given in the IPCC Good Practice Guidance report (2003), especially in section 4.3. The data collected with the guidance presented here can be used to obtain estimates of emission factors as described in section 2.4

In **Section 2.3.2** presents a stratification of carbon stocks

In **Section 2.3.3** guidance is provided on: Which Tier Should be Used? The IPCC GL AFOLU allow for three Tiers with increasing complexity and costs of monitoring forest carbon stocks.

In **Section 2.3.4** the focus is on: Stratification by Carbon Stock. As previously discussed stratification is an essential step to allow an accurate, cost effective and creditable linkage between the remote sensing imagery estimates of areas deforested and estimates of carbon stocks and therefore emissions. In this section guidance is provided on potential methods for the stratification of a country's forests.

In **Section 2.3.5** guidance is given on the actual estimation of biomass Carbon Stocks of Forests Undergoing Change. Steps are given on how to devise and implement a forest carbon inventory.

## 2.3.2 Overview of carbon stocks, and issues related to C stocks

### 2.3.2.1 Issues related to carbon stocks

2.3.2.1.1 Fate of carbon pools as a result of deforestation and degradation

A forest is composed of pools of carbon stored in the living trees above and belowground, in dead matter including standing dead trees, down woody debris and litter, in non-tree understory vegetation and in the soil organic matter. When trees are cut down there are three destinations for the stored carbon – dead wood, wood products or the atmosphere.

- ❑ In all cases, following deforestation and degradation, the stock in living trees decreases.

- ❑ Where degradation has occurred this is often followed by a recovery unless continued anthropogenic pressure or altered ecologic conditions precludes tree regrowth.

- ❑ The decreased tree carbon stock can either result in increased dead wood, increased wood products or immediate emissions.

- ❑ Dead wood stocks may be allowed to decompose over time or may, after a given period, be burned leading to further emissions.

- ❑ Wood products over time decompose, burned, or are retired to land fill.

- ❑ Where deforestation occurs, trees can be replaced by non-tree vegetation such as grasses or crops. In this case, the new land-use has consistently lower plant biomass and often lower soil carbon, particularly when converted to annual crops.

- ❑ Where a fallow cycle results, then periods of crops are interspersed with periods of forest regrowth that may or may not reach the threshold for definition as forest.

Figure 2.3.1. Fate of existing forest carbon stocks after deforestation in (sub-) tropical regions.
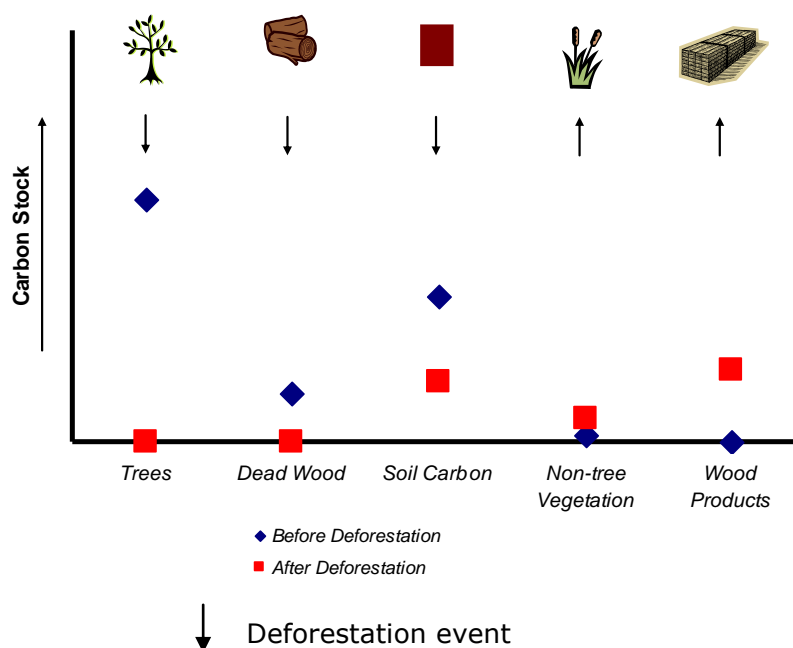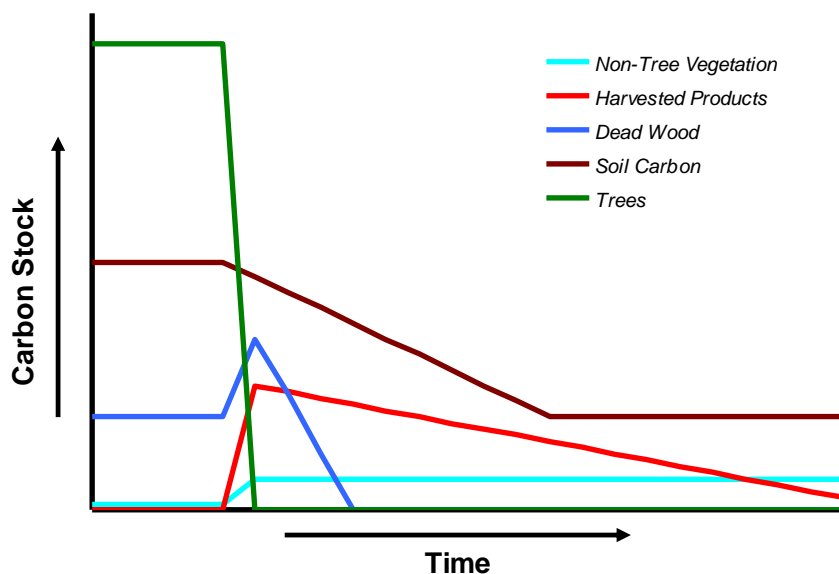
Note: harvested wood products do not remain the same place

2.3.2.1.2 The need for stratification and how it relates to remote sensing data

Carbon stocks vary by forest type, for example tropical pine forests will have a different stock than tropical broadleaf forests which will again have different stock than woodlands or mangrove forests. Even within broadleaf tropical forests, stocks will vary greatly with elevation, rainfall and soil type. Then even within a given forest type in a given location the degree of human disturbance will lead to further differences in stocks. The resolution of most readily and inexpensively available remote sensing imagery is not good enough to differentiate between different forest types or even between disturbed and undisturbed forest, and thus cannot differentiate different forest carbon stocks. However, stratifying forests is important for obtaining forest carbon stock data –stratifying into relatively homogeneous forest cover units with respect to their carbon stocks can result in a more cost effective field sampling design and more precise and accurate estimates of carbon stocks across a landscape (see more on this topic below in section 2.3.4).

2.3.3 Which Tier should be used?

2.3.3.1 Explanation of IPCC Tiers

The IPCC GPG and AFOLU Guidelines present three general approaches for estimating emissions/removals of greenhouse gases, known as "Tiers" ranging from 1 to 3 representing increasing levels of data requirements and analytical complexity. Despite differences in approach among the three tiers, all tiers have in common their adherence to IPCC good practice concepts of transparency, completeness, consistency, comparability, and accuracy.

Tier 1 requires no new data collection to generate estimates of forest biomass. Default values for forest biomass and forest biomass mean annual increment (MAI) are obtained from the IPCC Emission Factor Data Base (EFDB), corresponding to broad continental forest types (e.g. African tropical rainforest). Tier 1 estimates thus provide limited resolution of how forest biomass varies sub-nationally and have a large error range (~ +/- 50% or more) for growing stock in developing countries (Box 2.3.1). The former is

important because deforestation and degradation tend to be localized and hence may affect subsets of forest that differ consistently from a larger scale average (Figure 2.3.2). Tier 1 also uses simplified assumptions to calculate net emissions. For deforestation, Tier 1 uses the simplified assumption of instantaneous emissions from woody vegetation, litter and dead wood. To estimate emissions from degradation (i.e. Forest remaining as Forest), Tier 1 applies the gain-loss method (see Chapter 1) using a default MAI combined with losses reported from wood removals and disturbances, with transfers of biomass to dead organic matter estimated using default equations.

**Box 2.3.1. Error in Carbon Stocks from Tier 1 Reporting**

To illustrate the error in applying Tier 1 carbon stocks for the carbon element of a REDD+ system, a comparison is made here between the Tier 1 result and the carbon stock estimated from on-the-ground IPCC Good Practice-conforming plot measurements from six sites around the world. As can be seen in the table below, the IPCC Tier 1 predicted stocks range from 33 % higher to 44 % lower than a mean derived from multiple plot measurements in the given forest type.

Location	IPCC Definition	Tier 1 Default (t C/ha)	Plot Measurements (t C/ha)	Tier 1 as % of Plot Measurements
Brazil	Tropical Rainforest, North and South America	150	218	-31
Mexico	Temperate Mountain Systems, North and South America	65	49	+33
Indonesia	Tropical Rainforest Asia Insular	175	212	-17
Republic of Congo	Tropical rainforest Africa	155	277	-44
Republic of Guinea	Tropical rainforest Africa	155	209	-26
Madagascar	Tropical rainforest Africa	155	148	+5

Figure 2.3.2 below illustrates a hypothetical forest area, with a subset of the overall forest, or strata, denoted in light green. Despite the fact that the forest overall (including the light green strata) has, say, an accurate and precise mean biomass stock of 150 t C/ha, the light green strata alone has a significantly different mean biomass carbon stock (50 t C/ha). Because deforestation often takes place along "fronts" (e.g. agricultural frontiers) that may represent different subsets from a broad forest type (like the light green strata at the periphery here) a spatial resolution of forest biomass carbon stocks is required to accurately assign stocks to where loss of forest cover takes place. Assuming deforestation was taking place in the light green area only and the analyst was not aware of the different strata, applying the overall forest stock to the light green strata alone would give inaccurate results, and that source of uncertainty could only be discerned by subsequent ground-truthing.

Figure 2.3.2 also demonstrates the inadequacies of extrapolating localized data across a broad forest area, and hence the need to stratify forests according to expected carbon stocks and to augment limited existing datasets (e.g. forest inventories and research studies conducted locally) with supplemental data collection.

Figure 2.3.2. A hypothetical forest area, with a subset of the overall forest, or strata, denoted in light green.
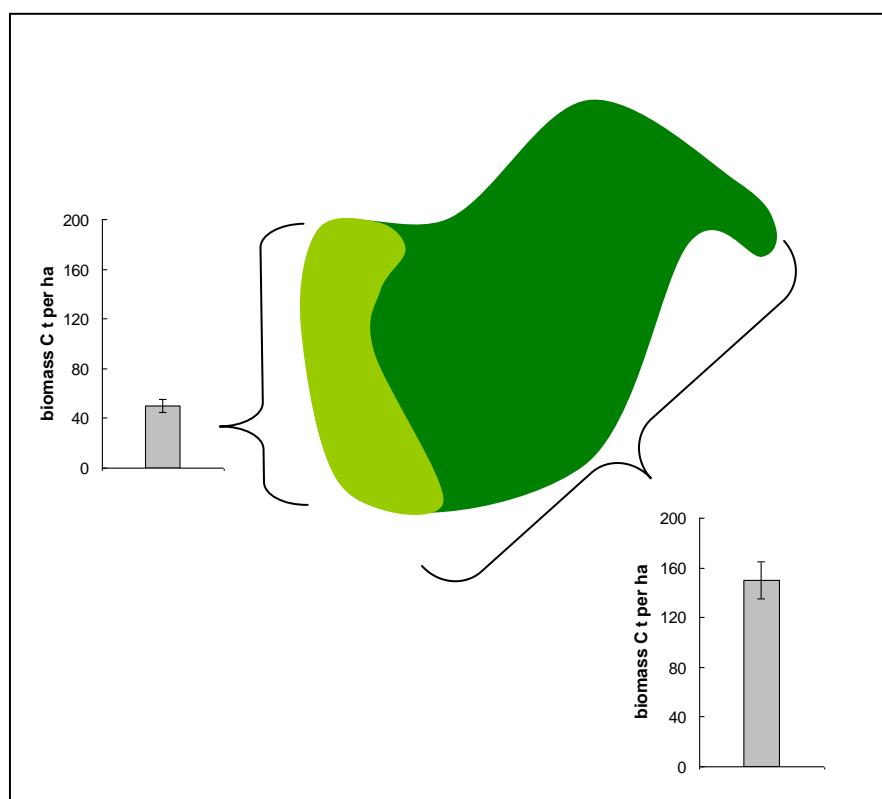
At the other extreme, Tier 3 is the most rigorous approach associated with the highest level of effort. Tier 3 uses actual forest carbon inventories with repeated measures to directly measure changes in forest biomass and/or uses well parameterized models in combination with plot data. Tier 3 often focuses on measurements of trees only, and uses region/forest specific default data and modelling for the other pools. The Tier 3 approach requires long-term commitments of resources and personnel, generally involving the establishment of a permanent organization to house the program (see section 3.2). The Tier 3 approach can thus be expensive in the developing country context, particularly where only a single objective (estimating emissions of greenhouse gases) supports the implementation costs. Unlike Tier 1, Tier 3 does not assume immediate emissions from deforestation, instead modelling transfers and releases among pools that more accurately reflect how emissions are realized over time. To estimate emissions from degradation, in contrast to Tier 1, a Tier 3 uses the stock difference approach where change in forest biomass stocks is directly estimated from repeated measures possibly in combination with models.

Tier 2 is akin to Tier 1 in that it employs static forest biomass information, but it also improves on that approach by using country-specific data (i.e. collected within the national boundary), and by resolving forest biomass at finer scales through the delineation of more detailed strata. Also, like Tier 3, Tier 2 can modify the Tier 1 assumption that carbon stocks in woody vegetation, litter and deadwood are immediately emitted following deforestation (i.e. that stocks after conversion are zero), and instead develop disturbance matrices that model retention, transfers (e.g. from woody biomass to dead wood/litter) and releases (e.g. through decomposition and burning) among pools. For degradation, in the absence of repeated measures from a representative inventory, Tier 2 uses the gain-loss method using locally-derived data on mean annual increment. Done well, a Tier 2 approach can yield significant improvements over Tier 1 in reducing uncertainty, and Tier 2 does not require the sustained institutional backing.

2.3.3.2 Data needs for each Tier

The availability of data is another important consideration in the selection of an appropriate Tier. Tier 1 has essentially no data collection needs beyond consulting the IPCC tables and EFDB, while Tier 3 requires mobilization of resources where no national data collection systems are in place (i.e. most developing countries). Data needs for each Tier are summarized in Table 2.3.1.

Table 2.3.1. Data needs for meeting the requirements of the three IPCC Tiers.

Tier	Data needs/examples of appropriate biomass data
Tier 1 (basic)	Default MAI* (for degradation) and/or forest biomass stock (for deforestation) values for broad continental forest types—IPCC includes six classes for each continental area to encompass differences in elevation and general climatic zone; default values given for all vegetation-based pools
Tier 2 (intermediate)	MAI* and/or forest volume or biomass values from existing forest inventories and/or ecological studies. Default values provided for all non-tree pools Newly-collected forest biomass data.
Tier 3 (most demanding)	Repeated measurements of trees from plots and/or calibrated process models. Can use default data for other pools stratified by in-country regions and forest type, or estimates from process models.

* MAI = Mean annual increment of tree growth

2.3.3.3 Selection of Tier

Tiers should be selected on the basis of goals (e.g. accurate and precise estimates of emissions reductions in the context of a performance-based incentives framework; conservative estimate subject to deductions), the significance of the target source/sink, available data, and analytical capability.

The IPCC recommends that it is good practice to use higher Tiers for the measurement of significant sources/sinks. To more clearly specify levels of data collection and analytical rigor among sources/sinks of emissions/removals, the IPCC Guidelines provide guidance on the identification of "Key Categories" (see section 1.2.3 for more discussion of this topic). Key categories are sources/sinks of emissions/removals that contribute substantially to the overall national inventory and/or national inventory trends, and/or are key sources of uncertainty in quantifying overall inventory amounts or trends.

Due to the balance of costs and the requirement for accuracy/precision in the carbon component of emission inventories, a Tier 2 methodology for carbon stock monitoring will likely be the most widely used in both for setting the reference level and for future reporting of net emissions from deforestation and degradation. Although it is suggested that a Tier 3 methodology be the level to aim for key categories and pools, in practice Tier 3 may be too costly to be widely used, at least in the near term. And, a statistically well designed system for Tier 2 data collection for estimating emission factors could practically be as good as a Tier 3 level.

On the other hand, Tier 1 will not deliver the accurate and precise estimates needed for key categories/pools by any mechanism in which economic incentives are foreseen. However, the principle of conservativeness will likely represent a fundamental instrument to ensure environmental integrity of REDD+ estimates. In that case, a tier lower than required could be used – or a carbon pool could be ignored - if it can be soundly demonstrated that the overall estimate of reduced emissions are underestimated (further explanation is given in section 2.8.4).

Different tiers can be applied to different pools where they have a lower importance. For example, where preliminary observations demonstrate that emissions from the litter or dead wood or soil carbon pool constitute less than 20% of emissions from deforestation, the Tier 1 approach using default transfers and decomposition rates would be justified for application to that pool.

2.3.4 Stratification by carbon stocks

Stratification refers to the division of any heterogeneous landscape into distinct sub-sections (or strata) based on some common grouping factor. In this case, the grouping factor is the stock of carbon in the vegetation. If multiple forest types are present across a country, stratification is the first step in a well-designed sampling scheme for estimating carbon emissions associated with deforestation and degradation over both large and small areas. Stratification is the critical step that will allow the association of a given area of deforestation and degradation with an appropriate carbon stock for the calculation of emissions.

2.3.4.1 Why stratify?

Different carbon stocks exist in different forest types and ecoregions depending on physical factors (e.g., precipitation regime, temperature, soil type, topography), biological factors (tree species composition, stand age, stand density) and anthropogenic factors (disturbance history, logging intensity). For example, secondary forests have lower carbon stocks than mature forests and logged forests have lower carbon stocks than unlogged forests. Associating a given area of deforestation with a specific carbon stock that is relevant to the location that is deforested or degraded will result in more accurate and precise estimates of carbon losses. This is the case for all levels of deforestation assessment from a very coarse Tier 1 assessment to a highly detailed Tier 3 assessment.

Because ground sampling is usually required to determine appropriate carbon estimates to apply to specific areas of deforestation or degradation, stratifying an area by its carbon stocks can **increase accuracy and precision and reduce costs**. National carbon accounting needs to emphasize a system in which stratification and refinement are based on carbon content (or expected change in carbon content) of specific forest types, not necessarily of forest vegetation. For example, the carbon stocks of a "tropical rain forest" (one vegetation class) may be vastly different with respect to carbon stocks depending on its geographic location and degree of disturbance within a given country.

2.3.4.2 Approaches to stratification

There are two possible approaches for stratifying forests for national carbon accounting, both of which require some spatial information on forest cover within a country. In Approach A, all of a country's forests are stratified 'up-front' and carbon stock estimates are made to produce a country-wide map of forest carbon stocks. At future monitoring events, only the activity data need to be monitored and combined with the pre-estimated carbon stock values. Such a map would then need to be updated periodically—at least once per commitment period. In Approach B, a full land cover map of the whole country does not need to be created. Rather, carbon estimates are made at each

monitoring event only in those forests strata that have undergone change. Which approach to use depends on a country's access to relevant and up-to-date data as well as its financial and technological resources. See Box 2.3.2 that provides a decision tree that can be used to select which stratification approach to use. Details of each approach are outlined below.

Box 2.3.2. Decision tree for stratification approach
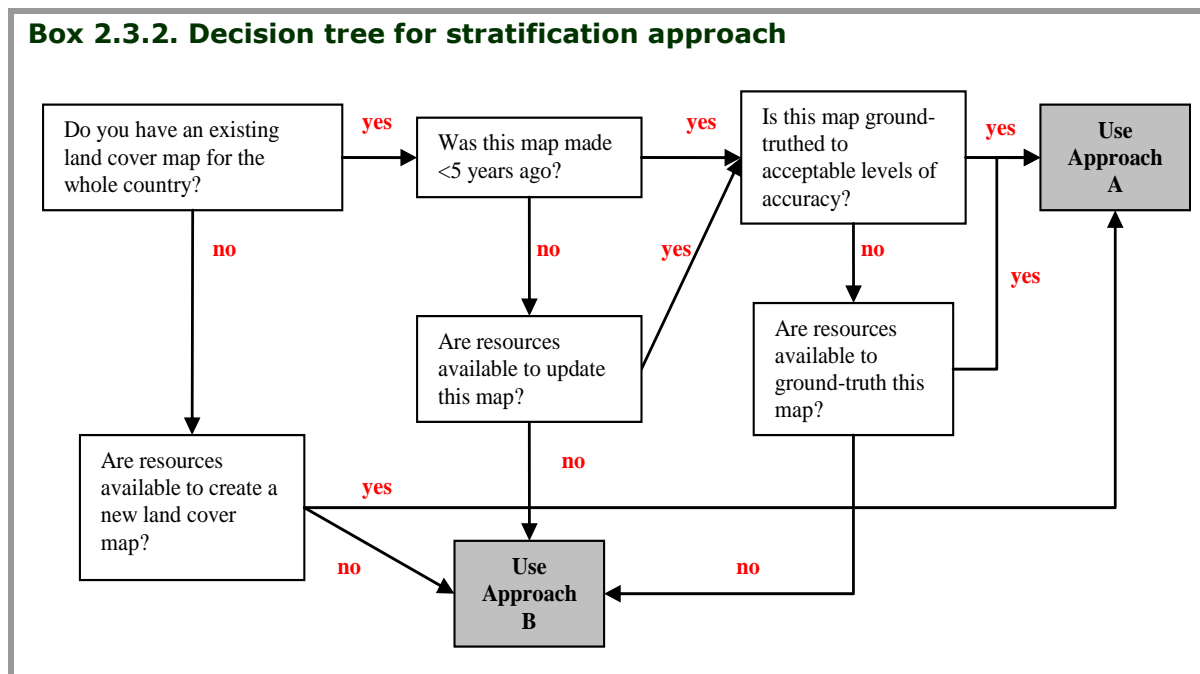
Approach A: 'Up-front' stratification using existing or updated land cover maps

The first step in stratifying by carbon stocks is to determine whether a national land cover or land use map already exists. This can be done by consulting with government agencies, forestry experts, universities, the FAO, internet, and the like who may have created these maps for other purposes.

Before using the existing land cover or land use map for stratification, its quality and relevance should be assessed. For example:

❑ When was the map created? Land cover change is often rapid and therefore a land cover map that was created more than five years ago is most likely out-of-date and no longer relevant. If this is the case, a new land cover map should be created. To participate in REDD+ activities it is likely a country will need to have at least a land cover map for a relatively recent time (benchmark map—see section 2.1).

❑ Is the existing map at an appropriate resolution for your country's size and land cover distribution? Land cover maps derived from coarse-resolution satellite imagery may not be detailed enough for very small countries and/or for countries with a highly patchy distribution of forest area. For most countries, land cover maps derived from medium-resolution imagery (e.g., 30-m resolution Landsat imagery) are adequate (see section 2.1).

❑ Is the map ground validated for accuracy? An accuracy assessment should be carried out before using any land cover map in additional analyses. Guidance on assessing the accuracy of remote sensing data is given in section 2.7.

Land cover and land use maps are sometimes produced for different purposes and therefore the classification may not be fully useable in their current form. For example, a land use map may classify all forest types as one broad 'forest' category that would not

be valuable for carbon stratification unless more detailed information was available to supplement this map. Indicator maps are valuable for adding detail to broadly defined forest categories (see Box 2.3.3 for examples), but should be used judiciously to avoid overcomplicating the issue. In most cases, overlaying one or two indicator maps (elevation and distance to transportation networks, for example) with a forest/non-forest land cover map should be adequate for delineating forest strata by carbon stocks, though this would need to be confirmed with field data.
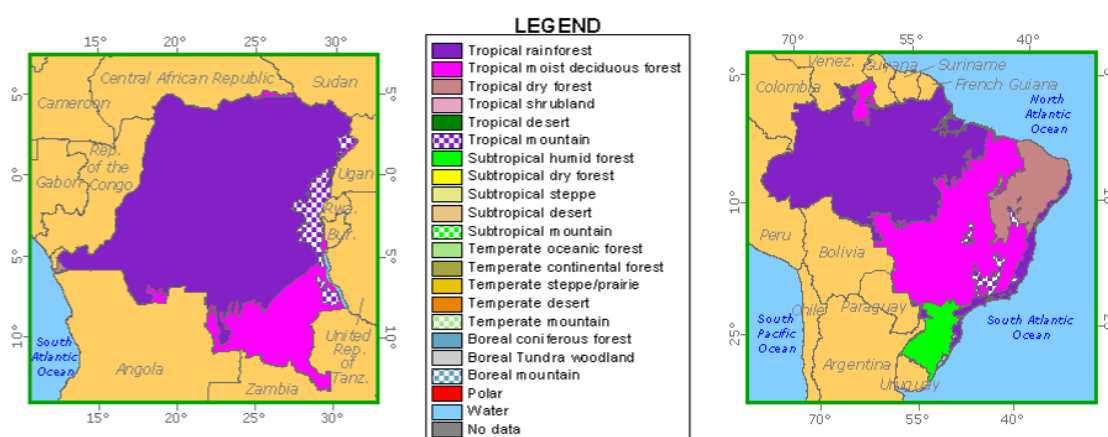
Once strata are delineated on a ground-validated land cover map and forest types have been identified, carbon stocks are estimated for each stratum using appropriate measuring and monitoring methods. A national map of forest carbon stocks can then be created (see section 2.3.4).

Box 2.3.3. Examples of maps on which a land use stratification can be built

Ecological zone maps

One option for countries with virtually no data on carbon stocks is to stratify the country initially by ecological zone or ecoregion using global datasets. Examples of these maps include:

1. Holdridge life zones (http://geodata.grid.unep.ch/)

2. WWF ecoregions (http://www.worldwildlife.org/science/data/terreco.cfm)

3. FAO ecological zones (http://www.fao.org/geonetwork/srv/en/main.home, type 'ecological zones' in search box)

 Indicator maps

After ecological zone maps are overlain with maps of forest cover to delineate where forests within different ecological zones are located, there are several indicators that could be used for further stratification. These indicators can be either biophysically- or anthropogenically-based:

Biophysical indicator maps	**Anthropogenic indicator maps**
Elevation	Distance to deforested land or forest edge
Topography (slope and aspect)	Distance to towns and villages
Soils	Proximity to transportation networks
	Rural population density
	Areas of protected forests

In Approach A, all of the carbon estimates would be made once, up-front, i.e., at the beginning of monitoring program, and no additional carbon estimates would be

necessary for the remainder of the monitoring or commitment period - only the activity data would need to be monitored. This does assume that the carbon stocks in the original forests being monitored would not change much over about 10 years—such a situation is likely to exist where most of the forests are relatively intact, have been subject to low intensity selective logging in the past, no major infrastructure exists in the areas, and/or are at a late secondary stage (> 40-50 years). When the forests in question do not meet the aforementioned criteria, then new estimates of the carbon stocks could be made based on measurements taken more frequently—up to less than 10 years, or even more frequently if the forests are degrading.

As ecological zone maps are a global product, they tend to be very broad and hence certain features of the landscape that affect carbon stocks within a country are not accounted for. For example, a country with mountainous terrain would benefit from using elevation data (such as a digital elevation model) to stratify ecological zones into different elevational sub-strata because forest biomass is known to decrease with elevation. Another example would be to stratify the ecological zone map by soil type as forests on loamy soils tend to have higher growth potential than those on very sandy or very clayey soils. If forest degradation is common in your country, stratifying ecological zones by distance to towns and villages or to transportation networks may be useful. An example of how to stratify a country with limited data is shown in Box 2.3.4.
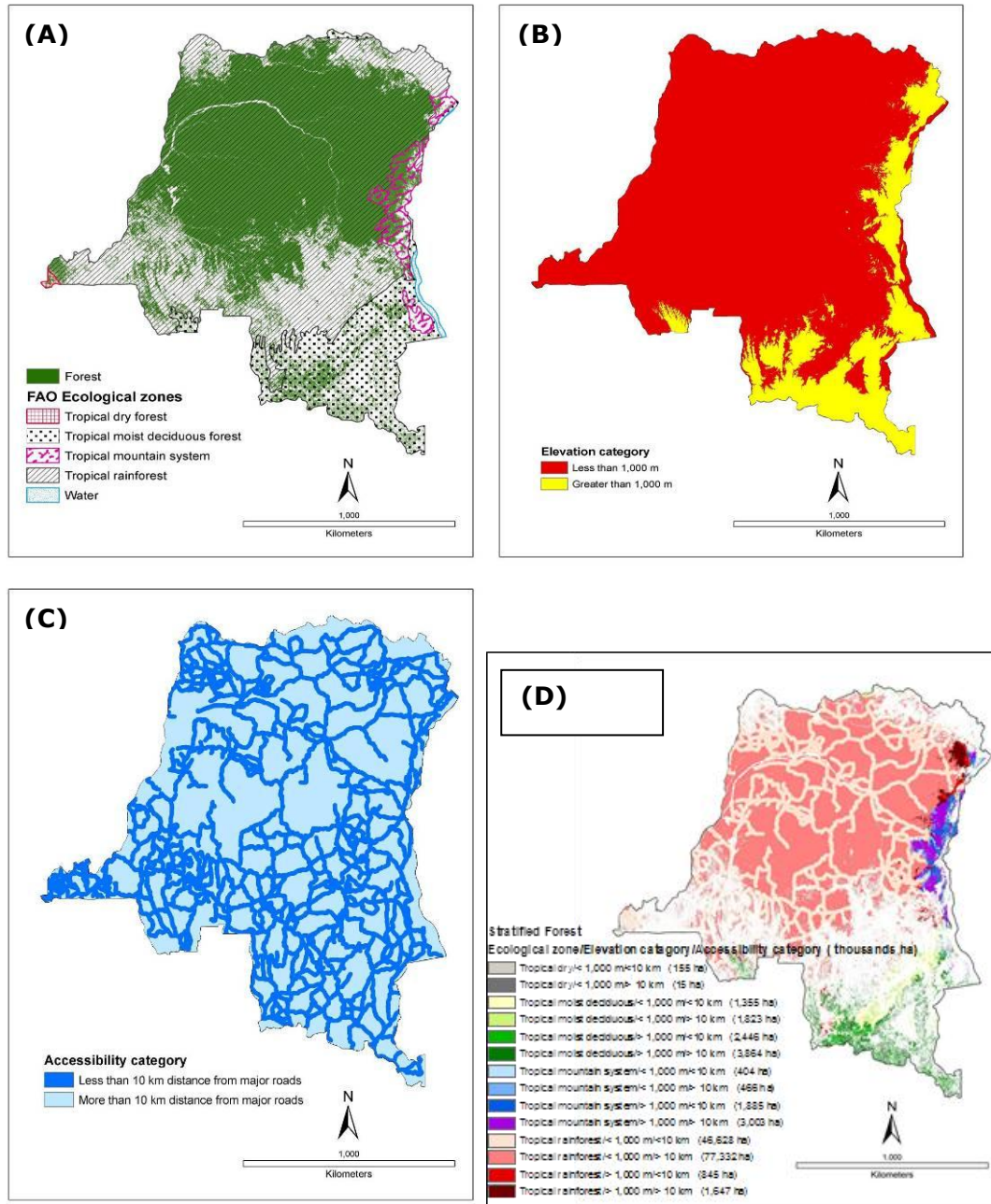
Box 2.3.4. Forest stratification in countries with limited data availability

An example stratification scheme is shown here for the Democratic Republic of Congo.

Step 1. Overlay a map of forest cover with an ecological zone map (A).

Step 2. Select indicator maps. For this example, elevation (B) and distance to roads (C) were chosen as indicators.

Step 3. Combine all factors to create a map of forest strata (D).

(A)

Forest
FAO Ecological zones
Tropical dry forest
Tropical moist deciduous forest
Tropical mountain system
Tropical rainforest
Water

1,000
Kilometers

(B)

Elevation category
Less than 1,000 m
Greater than 1,000 m

1,000
Kilometers

(C)

Accessibility category
Less than 10 km distance from major roads
More than 10 km distance from major roads

1,000
Kilometers

(D)

Stratified Forest
Ecological zone/Elevation catagory/Accessibility category (thousands ha)
Tropical dry/< 1,000 m/<10 km   (155 ha)
Tropical dry/< 1,000 m/> 10 km   (15 ha)
Tropical moist deciduous/< 1,000 m/< 10 km   (1,355 ha)
Tropical moist deciduous/< 1,000 m/> 10 km   (1,823 ha)
Tropical moist deciduous/> 1,000 m/< 10 km   (2,446 ha)
Tropical moist deciduous/> 1,000 m/> 10 km   (3,864 ha)
Tropical mountain system/< 1,000 m/< 10 km   (404 ha)
Tropical mountain system/< 1,000 m/> 10km   (466 ha)
Tropical mountain system/> 1,000 m/< 10 km   (1,885 ha)
Tropical mountain system/> 1,000 m/> 10km   (3,003 ha)
Tropical rainforest/< 1,000 m/<10 km   (46,628 ha)
Tropical rainforest/< 1,000 m/> 10 km   (77,332 ha)
Tropical rainforest/> 1,000 m/<10 km   (845 ha)
Tropical rainforest/> 1,000 m/> 10 km   (1,647 ha)

1,000
Kilometers

Approach B: Continuous stratification based on a continuous carbon inventory

Where wall-to-wall land cover mapping is not possible for stratifying forest area within a country by carbon stocks, regularly-timed "inventories" can be made by sampling only the areas subject to deforestation, degradation, and/or enhancement. Using this

approach, a full land cover map for the whole country is not necessary because carbon assessment occurs only where land cover change occurred (forest to non-forest, or intact to degraded forest in some cases). Carbon measurements can then be made in neighbouring pixels that have the same reflectance/textural characteristics as the pixels that had undergone change in the previous interval, serving as proxies for the sites deforested or degraded, and carbon losses can be calculated.

This approach is likely the least expensive option as long as neighbouring pixels to be measured are relatively easy to access by field teams. However, this approach is not recommended when vast areas of contiguous forest are converted to non-forest, because the forest stocks may have been too spatially variable to estimate a single proxy carbon value for the entire forest area that was converted. If this is the case, a conservative approach would be to use the lowest carbon stock estimate for the forest area that was converted to calculate emissions in the reference level and the highest carbon stock estimate in the monitoring phase.

2.3.5 Estimation of carbon stocks of forests undergoing change

2.3.5.1 Decisions on which carbon pools to include

The decision on which carbon pools to monitor as part of a REDD+ accounting scheme will likely be governed by the following factors:

- ❑ Available financial resources
- ❑ Availability of existing data
- ❑ Ease and cost of measurement
- ❑ The magnitude of potential change in the pool
- ❑ The principle of conservativeness

Above all is the principle of conservativeness. This principle ensures that reports of decreases in emissions are not overstated. **Clearly for this purpose both reference level and subsequent estimations must include exactly the same pools.** Conservativeness also allows for pools to be omitted except for the dominant tree carbon pool and a precedent exists for Parties to select which pools to monitor within the Kyoto Protocol and Marrakesh Accords (see section 2.8.4 for further discussion on conservativeness). For example, if dead wood or wood products are omitted then the assumption must be that all the carbon sequestered in the tree is immediately emitted and thus reduction in emissions from deforestation or degradation is under-estimated. Likewise if CO_2 emitted from the soil is excluded as a source of emissions; and as long as this exclusion is constant between the reference level and later estimations, then no exaggeration of emissions reductions occurs.

2.3.5.1.1 Key pools

The second deciding factor on which carbon pools to include should be the relative importance of the expected change in each of the carbon pools caused by deforestation and degradation. The magnitude of the carbon pool basically represents the magnitude of the emissions for deforestation as it is typically assumed that most of the pool is oxidized, either on or off site. For degradation the relationship is not as clear as usually only the trees are affected for most causes of degradation.

In all cases it will make sense to include trees, as trees are relatively easy to measure and will always represent a significant proportion of the total carbon stock. The remaining pools will represent varying proportions of total carbon depending on local

conditions. For example, belowground biomass carbon (roots) and soil carbon to 30 cm depth represents 26% of total carbon stock in estimates in tropical lowland forests of Bolivia but more than 50 % in the peat forests of Indonesia (Figure 2.3.3 a & b[24]). It is also possible that which pools are included or not varies by forest type/strata within a country. It is possible that say forest type A in a given country could have relatively high carbon stocks in the dead wood and litter pools, whereas forest type B in the country could have low quantities in these pools—in this case it might make sense to measure these pools in the forest A but not B as the emissions from deforestation would be higher in A than in B. In other words, which pools are selected for monitoring do not need to be the same for all forest types within a country.

Figure 2.3.3. LEFT- Proportion of total stock (202 t C/ha) in each carbon pool in Noel Kempff Climate Action project (a pilot carbon project), Bolivia, and RIGHT- Proportion of total stock (236 t C/ha) in each carbon pool in peat forest in Central Kalimantan, Indonesia (active peat includes soil organic carbon, live and dead roots, and decomposing materials).
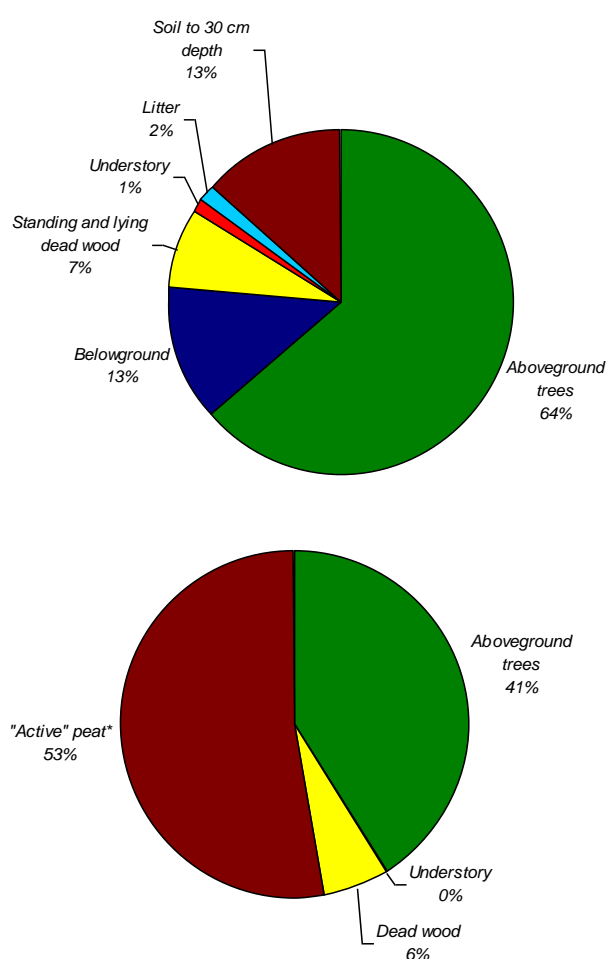
Pools can be divided by ecosystem and land use change type into key categories (large carbon source) or minor categories (small carbon source). Key categories represent pools that could account for more than 20% of the total emissions resulting from the deforestation or degradation (Table 2.3.2).

---

[24]Brown, S. 2002, Measuring, monitoring, and verification of carbon benefits for forest-based projects. Phil. Trans. R. Soc. Lond. A. 360: 1669-1683, and unpublished data from measurements by Winrock

Table 2.3.2. Broad guidance on key categories of carbon pools for determining assessment emphasis. Key category is defined as pools potentially responsible for more than 20% of total emission resulting from the deforestation or degradation.

	Biomass		Dead organic matter		Soils
	Aboveground	Below-ground	Dead wood	Litter	Soil organic matter
Deforestation					
To cropland	KEY	KEY	(KEY)		KEY
To pasture	KEY	KEY	(KEY)		
To shifting cultivation	KEY	KEY	(KEY)		
Degradation					
Degradation	KEY	KEY	(KEY)		

Certain pools such as soil carbon or even down dead material tend to be quite variable and can be relatively time consuming and costly to measure. The decision to include these pools would therefore be made based on whether they represent a key carbon source and available financial resources.

Soils will represent a key category in peat swamp forests and mangrove forests where carbon emissions will be high when deforested and drained (see section 2.5). For forests on mineral soils with high organic carbon content and deforestation is to cropland, as much as 30-40% of the total soil organic matter stock can be lost in the top 30 cm or so during the first 5 years. Where deforestation is to pasture or shifting cultivation, the science does not support a large drop in soil carbon stocks, and thus change in soil carbon stocks would not represent a key source.

Dead wood is a key source in old growth forest where it can represent more than 10% of total biomass, but in young successional forests, for example, it will not be a key category.

For carbon pools representing a fraction of the total (<20 %) it may be possible to include them at low cost if good default data, validated with local measures, are available.

Box 2.3.5 provides examples that illustrate the scale of potential emissions from just the aboveground biomass pool following deforestation and degradation in Bolivia, the Republic of Congo and Indonesia.

2.3.5.1.2 Selecting carbon measurement pools:

Step 1: Include aboveground tree biomass

All assessments should include aboveground tree biomass as the carbon stock in this pool is simple to measure and estimate and will almost always dominate carbon stock changes

Step 2: Include belowground tree biomass

Belowground tree biomass (roots) is almost never measured, but instead is included through a relationship to aboveground biomass (usually a root-to-shoot ratio). If the vegetation strata correspond with tropical or subtropical types listed in Table 2.3.3 (modified from Table 2.2.4 in IPCC GL AFOLU (2006) to exclude non-forest or non-tropical values and to account for incorrect values) then it makes sense to include roots.

Table 2.3.3. Root to shoot ratios modified* from Table 4.4. in IPCC GL AFOLU.

Domain	Ecological Zone	Above-ground biomass	Root-to-shoot ratio	Range
Tropical	Tropical rainforest or humid forest	<125 t.ha-1	0.20	0.09-0.25
		>125 t.ha-1	0.24	0.22-0.33
	Tropical dry forest	<20 t.ha-1	0.56	0.28-0.68
		>20 t.ha-1	0.28	0.27-0.28
Subtropical	Subtropical humid forest	<125 t.ha-1	0.20	0.09-0.25
		>125 t.ha-1	0.24	0.22-0.33
	Subtropical dry forest	<20 t.ha-1	0.56	0.28-0.68
		>20 t.ha-1	0.28	0.27-0.28

*the modification corrects an error in the table for tropical rainforest or humid forest based on communications with Karel Mokany, the lead author of the peer reviewed paper from which the data were extracted.

Step 3: Assess the relative importance of additional carbon pools

Assessment of whether other carbon pools represent key sources can be conducted via a literature review, discussions with universities or even field measurements from a few pilot plots following methodological guidance already provided in many of the sources given in this section.

Step 4: Determine if resources are available to include additional pools

When deciding if additional pools should be included or not, it is important to remember that whichever pool has been included in the reference level the same pools shall be included in all future monitoring events. Although national or global default values can be used, if they are a key category they will make the overall estimates more uncertain. However, it is possible that once a pool is selected for monitoring, default values could be used initially with the idea of improving these values through time, but even if just a one-time measurement will be the basis of the monitoring scheme, there are costs associated with including additional pools. For example:

- ❑ for soil carbon—many samples of soil are collected and then must be analysed in a laboratory for bulk density and percent soil carbon
- ❑ for non-tree vegetation—destructive sampling is usually employed with samples collected and dried to determine biomass and carbon stock
- ❑ for down dead wood—stocks are usually assessed along a transect with the simultaneous collection and subsequent drying of samples for dead wood density

If the pool is a significant source of emissions as a result of deforestation or degradation it must be included in the assessment. An alternative to measurement for minor carbon pools (<20% of the total potential emission) is to include estimates from tables of default data with high integrity (peer-reviewed).

2.3.5.2 General approaches to estimation of carbon stocks

2.3.5.2.1 Step 1: Identify strata where assessment of carbon stocks is necessary

Not all forest strata are likely to undergo deforestation or degradation. For example, strata that are currently distant from existing deforested areas and/or inaccessible from roads or rivers are unlikely to be under immediate threat. Therefore, a carbon assessment of every forest stratum within a country would not be cost-effective because not all forests will undergo change.

For stratification approach B (described above where resources are limited), where and when to conduct a carbon assessment over each monitoring period is defined by the activity data, with measurements taking place in nearby areas that currently have the same reflectance as the changed pixels had prior to deforestation or degradation . For stratification approach A, the best strategy would be to invest in carbon stock assessments for strata where there is a history or future likelihood of degradation or deforestation, not for strata where there is little to no deforestation pressure (e.g. forests far away from roads and non-navigable rives and on poor soils).

SubStep 1 – For reference level (for approach B): establish sampling plans in areas representative of the areas with recorded deforestation and/or degradation.

SubStep 2 – For future monitoring for approach B: identify strata where deforestation and/or degradation are likely to occur. These will be strata adjoining existing deforested areas or degraded forest, and/or strata with human access via roads or easily navigable waterways. Establish sampling plans for these strata. For the current period, it is not necessary to invest in measuring forests that are hard to access such as areas that are distant to transportation routes, towns, villages and existing farmland, areas that are not

mapped for future concessions (e.g. timber extraction or mining concessions) and/or areas at high elevations.

2.3.5.2.2 Step 2: Assess existing data

It is likely that within most countries there will be some data already collected that could be used to define the carbon stocks of one or more strata. These data could be derived from a forest inventory or perhaps from past scientific studies. Proceed with incorporating these data if the following criteria are fulfilled:

❑ The data are less than 10 years old

❑ The data are derived from multiple measurement plots

❑ All species must be included in the inventories

❑ The minimum diameter for trees included is 30cm or less at breast height

❑ Data are sampled from good coverage of the strata over which they will be extrapolated

Existing data that meet the above criteria should be applied across the strata from which they were representatively sampled and not beyond that. The existing data will likely be in one of two forms:

❑ Forest inventory data

❑ Data from scientific studies

Forest inventory data

Typically forest inventories have an economic motivation. As a consequence, forest inventories worldwide are derived from good sampling design. If the inventory can be applied to a stratum, all species are included and the minimum diameter is 0 cm or less then the data will be a high enough quality with sufficiently low uncertainty for inclusion. Inventory data typically comes in two different forms:

Stand tables—these data from a traditional forest inventory are potentially the most useful from which estimates of the carbon stock of trees can be calculated. Stand tables generally include a tally of all trees in a series of diameter classes. The method basically involves estimating the biomass per average tree of each diameter (diameter at breast height, dbh) class of the stand table, multiplying by the number of trees in the class, and summing across all classes[25]. The mid-point diameter of the class can be used[26] in combination with an allometric biomass regression equation. Guidance on choice of equation and application of equations is widely available (for example see sources in Box 2.3.8). For the open-ended largest diameter classes it is not obvious what diameter to assign to that class. Sometimes additional information is included that allows educated estimates to be made, but this is often not the case. The default assumption should be to assume the same width of the diameter class and take the midpoint, for example if the highest class is >110 cm and the other class are in 10 cm bands, then the midpoint to apply to the highest class should be 115 cm.

---

[25] More details are given in Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper 143, Rome, Italy.

[26] If information on the basal area of all the trees in each diameter class is provided, instead of using the midpoint of the diameter class the quadratic mean diameter (QMD) can be used instead—this is the diameter of the tree with the average basal area (=basal area of trees in class/#trees).

It is important that the diameter classes are not overly large so as to decrease how representative the average tree biomass is for that class. Generally the rule should be that the width of diameter classes should not exceed 15 cm.

Sometimes, the stand tables only include trees with a minimum diameter of 30 cm or more, which essentially ignores a significant amount of carbon particularly for younger forests or heavily logged forests. To overcome the problem of such incomplete stand tables, an approach has been developed for estimating the number of trees in smaller diameter classes based on number of trees in larger classes[27]. It is recommended that the method described here (Box 2.2.6) be used for estimating the number of trees in one to two small classes only to complete a stand table to a minimum diameter of 10 cm.

Box 2.3.6. Adding diameter classes to truncated stand tables

DBH Class (cm)	Midpoint Diameter (cm)	Number of Stems per ha
10-19	15	-
20-29	25	-
30-39	35	35.1
40-49	45	11.8
50-59	55	4.7
...	...	...

dbh class 1= 30-39 cm, and dbh class 2= 40-49 cm

Ratio   = 35.1/11.8 = 2.97

Therefore, the number of trees in the 20-29 cm class is: 2.97 x 35.1 = 104.4

To calculate the 10-19 cm class: 104.4/35.1 = 2.97,

        2.97 x 104.4 = 310.6

The method is based on the concept that uneven-aged forest stands have a characteristic "inverse J-shaped" diameter distribution. These distributions have a large number of trees in the small classes and gradually decreasing numbers in medium to large classes. The best method is the one that estimated the number of trees in the missing smallest class as the ratio of the number of trees in dbh class 1 (the smallest reported class) to the number in dbh class 2 (the next smallest class) times the number in dbh class 1 (demonstrated in Box 2.3.6).

Stock tables—a table of the merchantable volume is sometimes available, often by diameter class or total per hectare. If stand tables are not available, it is likely that volume data are available if a forestry inventory has been conducted somewhere in the country. In many cases volumes given will be of just commercial species. If this is the case then these data cannot be used for estimating carbon stocks, as a large and unknown proportion of total volume and therefore total biomass is excluded.

Biomass density can be calculated from volume over bark of merchantable growing stock wood (VOB) by "expanding" this value to take into account the biomass of the other aboveground components—this is referred to as the biomass conversion and expansion

---

[27] Gillespie AJR, Brown S, Lugo AE (1992) Tropical forest biomass estimation from truncated stand tables. *Forest Ecology and Management* 48:69-88.

factor (BCEF). When using this approach and default values of the BCEF provided in the IPCC AFOLU, it is important that the definitions of VOB match. The values of BCEF for tropical forests in the AFOLU report are based on a definition of VOB as follows:

Inventoried volume over bark of free bole, i.e. from stump or buttress to crown point or first main branch. Inventoried volume must include all trees, whether presently commercial or not, with a minimum diameter of 10 cm at breast height or above buttress if this is higher.

Aboveground biomass (t/ha) is then estimated as follows: = VOB * BCEF[28]

where:

BCEF t/m³ = biomass conversion and expansion factor (ratio of aboveground oven-dry biomass of trees [t/ha] to merchantable growing stock volume over bark [m³/ha]).

Values of the BCEF are given in Table 4.5 of the IPCC AFOLU, and those relevant to tropical humid broadleaf and pine forests are shown in the Table 2.3.4.

Table 2.3.4. Values of BCEF (average and range) for application to volume data. (Modified from Table 4.5 in IPCC AFOLU)

Forest type	Growing stock volume –range (VOB, m³/ha)						
	<20	21-40	41-60	61-80	80-120	120-200	>200
Natural broadleaf	4.0	2.8	2.1	1.7	1.5	1.3	1.0
	2.5-12.0	1.8-304	1.2-2.5	1.2-2.2	1.0-1.8	0.9-1.6	0.7-1.1
Conifer	1.8	1.3	1.0	0.8	0.8	0.7	0.7
	1.4-2.4	1.0-1.5	0.8-1.2	0.7-1.2	0.6-1.0	1.6-0.9	0.6-0.9

In cases where the definition of VOB does not match exactly the definition given above, a range of BCEF values are given:

❑ If the definition of VOB also includes stem tops and large branches then the lower bound of the range for a given growing stock should be used

❑ If the definition of VOB has a large minimum top diameter or the VOB is comprised of trees with particularly high basic wood density then the upper bound of the range should be used

An alternative approach for using volume data from stock tables to estimate biomass of tropical humid broadleaf forests is based on the following equation:

Aboveground biomass (t/ha) = VOB * WD * BEF

Where VOB is the same as defined above, WD is the volume-weighted average wood density of the forest (t/m³) and BEF is the biomass expansion factor (ratio of aboveground oven-dry biomass of trees to oven-dry biomass of inventoried volume, dimensionless).

Analysis of inventory data (VOB and with corresponding biomass estimates) showed that that BEFs are significantly related to the corresponding biomass of the inventoried volume according to the following equations[29]:

---

[28] This method from the IPCC AFOLU replaces the one reported in the IPCC GPG. The GPG method uses a slightly different equation : AGB = VOB*wood density*BEF; where BEF, the biomass expansion factor, is the ratio of aboveground biomass to biomass of the merchantable volume in this case.

$$BEF = Exp\{3.213 - 0.506*Ln(BV)\} \text{ for } BV < 190 \text{ t/ha}$$

$$= 1.74 \qquad\qquad \text{for } BV \geq 190 \text{ t/ha}$$

Where BV is biomass of inventoried volume in t/ha, calculated as the product of VOB/ha (m3/ha) and wood density (t/m3).

Use of this relationship takes the guesswork out of the analysis as one value is produced from the equations rather than a range of values given by the IPCC AFOLU approach (Table 2.3.4). The equation shows that the BEF decreases with increasing BV, a pattern consistent with theoretical expectation. Even at very low values of BV (tending to zero) there will be a quantity of aboveground biomass but not commercial—thus the BEF will tend to be a very large value because there is a defined numerator and a very small denominator. At the other end of the relationship the BEF tends to a constant when the BV is large as happens when the biomass of the non-commercial component tends to be a relatively small and constant proportion of the total aboveground biomass, which is dominated by the biomass in the larger tree stems.

Forest inventories often report volumes to a minimum diameter greater than 10 cm. These inventories may be the only ones available. To allow the inclusion of these inventories, volume expansion factors (VEF) were developed[30]. After 10 cm, common minimum diameters for inventoried volumes range between 25 and 30 cm. Due to high uncertainty in extrapolating inventoried volume based on a minimum diameter of larger than 30 cm, inventories with a minimum diameter that is higher than 30 cm should not be used. Volume expansion factors range from about 1.1 to 2.5, and are related to the VOB30 as follows to allow conversion of VOB30 to a VOB10 equivalent:

$$VEF \quad = Exp\{1.300 - 0.209*Ln(VOB30)\} \text{ for } VOB30 < 250 \text{ m3/ha}$$

$$= 1.13 \qquad\qquad \text{for } VOB30 > 250 \text{ m3/ha}$$

See Box 2.3.7 for a demonstration of the use of the VEF correction factor and BCEF approach to estimate biomass density.

Box 2.3.7. Use of volume expansion factor (VEF) and biomass conversion and expansion factor (BCEF)

Tropical broadleaf forest with a VOB30 = 100 m³/ha

First: Calculate the VEF
 = Exp {1.300 - 0.209*Ln(100)} = 1.40

Second: Calculate VOB10
 = 100 m³/ha x 1.40 = 140 m³/ha

Third: Take the BCEF from the table above
 = Tropical hardwood with growing stock of 140 m³/ha = 1.3

Fourth: Calculate aboveground biomass density
 = 1.3 x 140
 = 182 t/ha

---

[29] Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper 143, Rome, Italy.

[30] Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper 143, Rome, Italy.

Data from scientific studies

Scientific evaluations of biomass, volume or carbon stock are conducted under multiple motivations that may or may not align with the stratum-based approach required for carbon stock assessments for deforestation and degradation.

Scientific plots may be used to represent the carbon stock of a stratum as long as there are multiple plots and the plots are randomly located. Many scientific plots will be in old growth forest and may provide a good representation of this stratum.

The acceptable level of uncertainty is undefined, but quality of research data could be illustrated by an uncertainty level of 20% or less (95% confidence equal to 20% of the mean or less). If this level is reached then these data could be applicable.

2.3.5.2.3 Step 3: Collect missing data

It is likely that even if data exist they will not cover all strata so in almost all situations a new measuring and monitoring plan will need to be designed and implemented to achieve a Tier 2 level. With careful planning this need not be an overly costly proposition.

The first step would be a decision on how many strata with deforestation or degradation in the reference level are at risk of deforestation or degradation, but do not have estimates of carbon stock. These strata should then be the focus of any future monitoring plan. Many resources are available or becoming available to assist countries in planning and implementing the collection of new data to enable them to estimate forest carbon stocks with high confidence (e.g. bilateral and multilateral organizations, FAO etc.), sources of such information and guidance is given in Box 2.3.8).

Box 2.3.8. Guidance on collecting new carbon stock data

Many resources are available to countries and organizations seeking to conduct carbon assessments of land use strata.

1. The Food and Agriculture Organization of the United Nations has been supporting forest inventories for more than 50 years—data from these inventories can be converted to C stocks using the methods given above. However, it would be useful in the implementation of new inventories that the actual dbh be measured and recorded for all trees, rather than reporting only stand/stock tables. Application of allometric equations commonly acceptable in carbon studies[31] to such data (by plots) would provide estimates of carbon stocks with lower uncertainty than estimates based on converting volume data as described above. The FAO National Forest Inventory Field Manual is available at:

   http://www.fao.org/docrep/008/ae578e00.htm

2. Specific guidance on field measurement of carbon stocks can be found in Chapter 4.3 of GPG LULUCF and also in the World Bank Sourcebook for LULUCF available at:
   http://carbonfinance.org/doc/LULUCF_sourcebook_compressed.pdf

3. Tools to guide collection of new forest carbon stock data are available at:
   http://www.winrock.org/Ecosystems/tools.asp?BU=9086

---

[31]E.g. Chave J et al. (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87-99.

Lacking in the sources given in Box 2.3.8 is guidance on how to improve the estimates of the total impacts on forest carbon stocks from degradation, particularly from various intensities of selective logging (whether legal or illegal). The IPCC AFOLU guidelines consider losses from the actual trees logged, but does not include losses from damage to residual trees nor from the construction of skid trails, roads and logging decks; gains from regrowth are included but with limited guidance on how to apply the regrowth factors. An outline of the steps needed to improve the estimates of carbon losses from selective logging are described in Box 2.3.9.

Box 2.3.9. Estimating carbon gains and losses from timber extraction

A model that illustrates the fate of live biomass and subsequent CO_2 emissions when a forest is selectively logged is shown below.
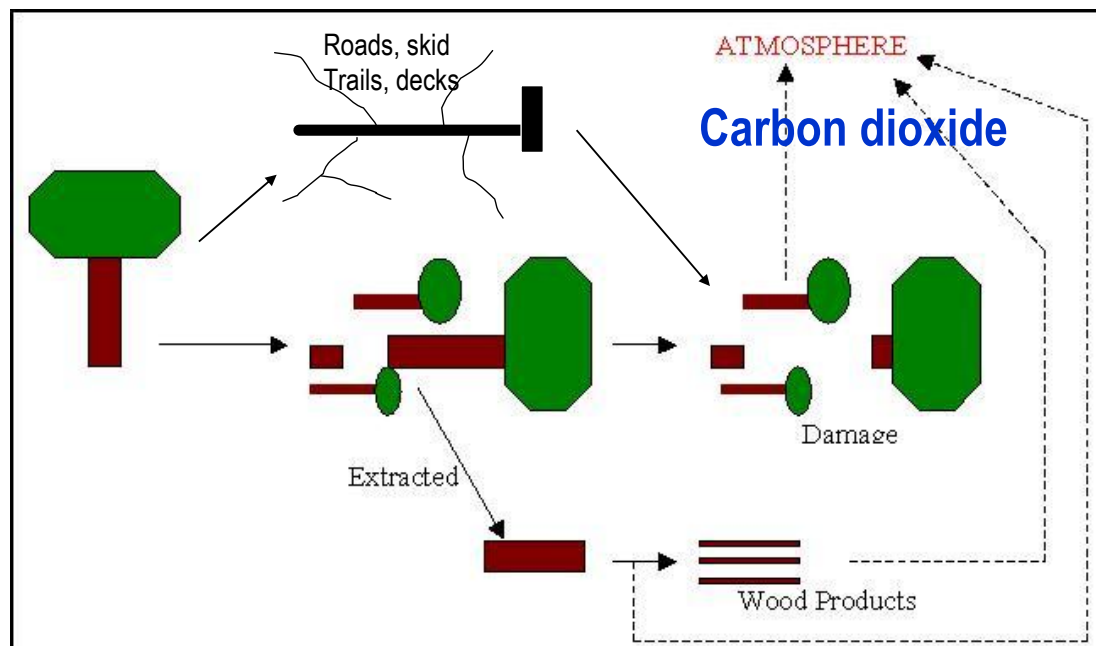
This model can be used for both harvesting of trees for timber or for fuel wood – in the latter case the wood products would be fuel wood or charcoal.

The total annual carbon loss is a function of: (i) the area logged in a given year; (ii) the amount of timber extracted per unit area per year; (iii) the amount of dead wood produced in a given year (from tops and stump of the harvested tree, mortality of the surrounding trees caused by the logging, and tree mortality from the skid trails, roads, and log landings), and (iv) the biomass that went into long term storage as wood products (Brown et al., 2011).

The equation to estimate net emissions in t C ha-1yr-1 is based on the IPCC gain-loss methodology as follows:

= RG - [Vol x WD x CF x (1-LTP)] +[Vol x LDF] + [AI x LIF]

Where:

RG = regrowth of the forest (t C ha-1yr-1)

Vol = volume of timber over bark extracted (m3/ha)

WD = wood density (t/m3)

CF = carbon fraction

LTP = proportion of extracted wood in long term products still in use after 100 yr (dimensionless)

LDF = logging damage factor—dead biomass left behind in gap from felled tree and collateral damage (t C/m3)

AI = area of logging infrastructure (length * width, ha)

LIF = logging infrastructure factor—dead biomass caused by construction of infrastructure (t C/ha)

The regrowth rate (RG) can only be applied to the area of gaps and a relatively narrow zone extending into the forest around the gap that would likely benefit from additional light and not to the total area under logging.

The LTP factor takes into account the fact that not all of the decrease in live biomass due to logging is emitted to the atmosphere as a carbon emission because a relatively large fraction of the harvested wood goes into long term wood products. However, even wood products are not a permanent storage of carbon—some of it goes into products that have short lives (some paper products), some turns over very slowly (e.g., construction timber and furniture), but all is eventually disposed of by burning, decomposition or buried in landfills. The time frame used in this equation is 100 yr based on the assumption that any wood still in use after this period can be considered permanent.

The data required to use this approach need to be collected from measurements made in tree felling gaps— preferably the gaps must just have been created before the field work or after a period of no more than 6 months. The reason for this is that it will be very difficult to unambiguously measure all the parameters needed to use the model. Also the amount of volume removed (either as timber or fuel wood) can be quantified by non-remote sensing methods (e.g. records of timber extracted per ha in a concession). The area of skid trails, logging roads, and log landings can be detected in fine to medium resolution satellite imagery using the approaches described in section 2.2 monitoring change in forest land remaining forest land or from extensive field measurements of the infrastructure components.

Creating a national look-up table

A cost-effective method for Approach A and Approach B stratifications may be to create a "national look-up table" for the country that will detail the carbon stock in each selected pool in each stratum. Look-up tables should ideally be updated periodically (e.g. each commitment period) to account for changing mean biomass stocks due to shifts in age distributions, climate, and or disturbance regimes. The look up table can then be used through time to detail the pre-deforestation or degradation stocks and estimated stocks after deforestation and degradation. An example is given in Box 2.3.10.

Box 2.3.10. A national look up table for deforestation and degradation

The following is a hypothetical look-up table for use with approach A or approach B stratification. We can assume that remote sensing analysis reveals that 800 ha of lowland forest were deforested to shifting agriculture and 500 ha of montane forest were degraded. Using the national look-up table results in the following:

The loss for deforestation would be

154 t C/ha – 37 t C/ha = 117 t C/ha x 800 ha =93,600 t C.

The loss for the degradation would be

130 t C/ha – 92 t C/ha = 38 t C/ha x 500 ha =19,000 t C

(Note that degradation will often have been caused by harvest and therefore emissions will be decreased if storage in long-term wood products, rather than by fuel wood extraction, was included—that is the harvested wood did not enter the atmosphere.)

Stratum	Aboveground Tree	Belowground Tree	Dead wood	Non-Tree	Total
Lowland Forest	110	23	18	3	154
Montane Forest	91	17	17	5	130
Open Woodland	48	10	6	8	72
Degraded Lowland Forest	70	15	18	4	107
Degraded Montane Forest	58	11	16	7	92
Degraded Woodland	28	6	6	6	46
Shifting Cultivation	20	5	5	7	37
Permanent Agriculture	0	0	0	4	4