SOURCEBOOK

Reducing Greenhouse Gas Emissions from Deforestation and Degradation in Developing Countries: A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting

GOFC-GOLD

REDUCING GREENHOUSE GAS EMISSIONS FROM DEFORESTATION AND DEGRADATION IN DEVELOPING COUNTRIES: A SOURCEBOOK OF METHODS AND PROCEDURES FOR MONITORING, MEASURING AND REPORTING

Background and Rationale for the Sourcebook

This sourcebook provides a consensus perspective from the global community of earth observation and carbon experts on methodological issues relating to quantifying the green house gas (GHG) impacts of implementing activities to reduce emissions from deforestation and degradation in developing countries (REDD). The UNFCCC negotiations and related country submissions on REDD in 2005-2007 have advocated that methodologies and tools become available for estimating emissions from deforestation with an acceptable level of certainty. Based on the current status of negotiations and UNFCCC approved methodologies, this sourcebook aims to provide additional explanation, clarification, and methodologies to support REDD early actions and readiness mechanisms for building national REDD monitoring systems. It emphasizes the role of satellite remote sensing as an important tool for monitoring changes in forest cover, and provides clarification on applying the IPCC Guidelines for reporting changes in forest carbon stocks at the national level.

The sourcebook is the outcome of an ad-hoc REDD working group of “Global Observation of Forest and Land Cover Dynamics” (GOFC-GOLD, www.fao.org/gtos/gofc-gold/), a technical panel of the Global Terrestrial Observing System (GTOS). The working group has been active since the initiation of the UNFCCC REDD process in 2005, has organized REDD expert workshops, and has contributed to related UNFCCC/SBSTA side events and GTOS submissions. GOFC-GOLD provides an independent expert platform for international cooperation and communication to formulate scientific consensus and provide technical input to the discussions and for implementation activities. A number of international experts in remote sensing and carbon measurement and accounting have contributed to the development of this sourcebook.

With political discussions and negotiations ongoing, the current document provides the starting point for defining an appropriate monitoring framework considering current technical capabilities to measure gross carbon emission from changes in forest cover by deforestation and degradation on the national level. This sourcebook is a living document and further methods and technical details can be specified and added with evolving political negotiations and decisions. Respective communities are invited to provide comments and feedback to evolve a more detailed and refined technical-guidelines document in the future. We acknowledge the following people for the comments which were made on the first version distributed in December 2007 in Bali: Margaret Skutsch, Sharon Gomez, David Shoch, Bill Stanley, Steven De Gryze, Albert Ackhurst and Doug Muchoney.

Authors

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This publication is the result of a joint voluntary effort from a number of experts from different institutions (that they may not necessarily represent). It is still an evolving document. The experts who contributed to the present version are listed under the chapter(s) to which they contributed.

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Specific acknowledgement is given to the contribution of Sandra Brown in preparing the first version of the sourcebook presented at UNFCCC COP 13 in Bali (December 2007).

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1 PURPOSE AND SCOPE OF THE SOURCEBOOK

This sourcebook is designed to be a guide to develop a reference emission and design a system for monitoring and estimating carbon dioxide emissions from deforestation and forest degradation at the national scale, based on the general requirements set by the United Nation Framework Convention on Climate Change (UNFCCC) and the specific methodologies for the land use and forest sectors provided by the Intergovernmental Panel on Climate Change (IPCC).

The sourcebook introduces users to: i) the key issues and challenges related to monitoring and estimating carbon emissions from deforestation and forest degradation; ii) the key methods provided in the 2003 IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (GPG-LULUCF) and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for Agriculture, Forestry and Other Land Uses (GL-AFOLU); iii) how these IPCC methods provide the steps needed to estimate emissions from deforestation and forest degradation and iv) the key issues and challenges related to reporting the estimated emissions.

The sourcebook provides transparent methods and procedures that are designed to produce accurate estimates of changes in forest area and carbon stocks and resulting emissions of carbon dioxide from deforestation and degradation, in a format that is user-friendly. It is intended to complement the GPG-LULUCF and AFOLU by providing additional explanation, clarification and enhanced methodologies for obtaining and analyzing key data.

The sourcebook is not designed as a primer on how to analyze remote sensing data nor how to collect field measurements of forest carbon stocks as it is expected that the users of this sourcebook would have some expertise in either of these areas.

The sourcebook was developed considering the following guiding principles:

- ☐ Relevance: Any monitoring system should provide an appropriate match between known REDD policy requirements and current technical capabilities. Further methods and technical details can be specified and added with evolving political negotiations and decisions.
- ☐ Comprehensiveness: The system should allow global applicability with implementation at the national level, and with approaches that have potential for sub-national activities.
- ☐ Consistency: Efforts have to consider previous related UNFCCC efforts and definitions.
- ☐ Efficiency: Proposed methods should allow cost-effective and timely implementation, and support early actions.
- ☐ Robustness: Monitoring should provide appropriate results based on sound scientific underpinnings and international technical consensus among expert groups.
- ☐ Transparency: The system must open and readily available for third party reviewers and the methodology applied must be replicable.

2 ISSUES AND CHALLENGES

The permanent conversion of forested to non-forested areas in developing countries has had a significant impact on the accumulation of greenhouse gases in the atmosphere[1], as has forest degradation caused by high impact logging, over-exploitation for fuelwood, intense grazing that reduces regeneration, wildfires, and forest fragmentation. If the emissions of methane (CH_4), nitrous oxide (N_2O), and other chemically reactive gases that result from subsequent uses of the land are considered in addition to carbon dioxide (CO_2) emissions, annual emissions from tropical deforestation during the 1990s accounted for about 15-25% of the total anthropogenic emissions of greenhouse gases[2].

For a number of reasons, activities to reduce such emissions are not accepted for generating creditable emissions reductions under the Kyoto Protocol. However, the compelling environmental rationale for their consideration has been crucial for the recent inclusion of the REDD issue (i.e., "Reducing Emissions from Deforestation and Forest Degradation in developing countries") in the UNFCCC agenda for a future global climate agreement[3], Although existing IPCC methodologies and UNFCCC reporting principles will represent the basis of any future REDD mechanism, fundamental methodological issues need to be urgently addressed in order to produce estimates that are "results based, demonstrable, transparent, and verifiable, and estimated consistently over time"[4] – this is the focus of this sourcebook.

2.1 LULUCF in the UNFCCC and Kyoto Protocol

Under the current rules for Annex I (i.e. industrialized) countries, the Land Use, Land Use Change and Forestry (LULUCF) sector is the only sector where the requirements for reporting emissions and removals are different between the UNFCCC and the Kyoto Protocol (Table 2.1). Indeed, unlike the reporting under the Convention - which includes all emissions/removals from LULUCF -, under the Kyoto Protocol the reporting and accounting of emissions/removals is mandatory only for the activities under Art. 3.3, while it is voluntary (i.e. eligible) for activities under Art. 3.4 (see Table 2.1). These LULUCF activities may be developed domestically by Annex I countries or via Kyoto Protocol's flexible instruments, including Afforestation/Reforestation projects under the "Clean Development Mechanism" (CDM) in non-Annex I (i.e. developing) countries. For the national inventories, estimating and reporting guidelines can be drawn from UNFCCC documents[5], the 1996 IPCC (revised) Guidelines, the 2003 Good Practice Guidance for LULUCF (GPG-LULUCF; Chapter 3 for UNFCCC reporting and Chapter 4 for methods specific to the Kyoto Protocol reporting).

The IPCC has also adopted a more recent set of estimation guidelines (2006 Guidelines) in which the Agriculture and LULUCF sectors are integrated to form the Agriculture, Land Use and Forestry (AFOLU) sector. Although these latest Guidelines should be still considered only a scientific publication, because the decision of their use for reporting under UNFCCC has not been taken yet, in this sourcebook we make frequent references to them (as GL-AFOLU) because they represent a relevant and updated source of methodological information.

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[1] De Fries et al. (2002); Houghton (2003); Achard et al. (2004)

[2] According to the IPCC AR4 (2007), $1.6\underline{+}0.9$ GtC yr^{-1} are emitted from land use changes (mainly tropical deforestation)

[3] Decision -/CP.13, http:/unfccc.int/files/meetings/cop_13/application/pdf/cp_bali_action.pdf

[4] Decision -/CP.13. http://unfccc.int/files/meetings/cop_13/application/pdf/cp_redd.pdf.

[5] For a broader overview of reporting principles and procedures under UNFCCC see Chapter 6.2.

Table 2.1: Existing frameworks for the Land Use, Land Use Change and Forestry (LULUCF) sector under the UNFCCC and the Kyoto Protocol.

Land Use, Land Use Change and Forestry		
UNFCCC (2003 GPG and 2006 GL-AFOLU)	**Kyoto**	**Kyoto-Flexibility**
Six land use classes and conversion between them: Forest lands Cropland Grassland Settlements Wetlands Other Land	**Article 3.3** Afforestation, Reforestation, Deforestation **Article 3.4** Cropland management Grazing land management Forest management Revegetation	**CDM** Afforestation Reforestation
Deforestation= forest converted to another land category	Controlled by the Rules and Modalities (including Definitions) of the Marrakesh Accords	

2.2 Definition of Forests, Deforestation and Degradation

For the new REDD mechanism, many terms, definitions and other elements are not yet clear. For example, although the terms 'deforestation' and 'forest degradation' are commonly used, they can widely vary among countries. As decisions for REDD will likely build on the current modalities under the UNFCCC and its Kyoto Protocol, current definitions and terms potentially represent a starting point for considering refined and/or additional definitions, if it will be needed.

For this reason, the definitions as used in UNFCCC and Kyoto Protocol context, potentially applicable to REDD after a negotiation process, are described below. Specifically, while for reporting under the UNFCCC only generic definitions on land uses were agreed on, the Marrakesh Accords (MA) prescribed a set of more specific definitions to be applied for LULUCF activities the Kyoto Protocol, although some flexibility is left to countries.

Forest land – Under the UNFCCC, this category includes all land with woody vegetation consistent with thresholds used to define Forest Land in the national greenhouse gas inventory. It also includes systems with a vegetation structure that does not, but *in situ* could potentially reach, the threshold values used by a country to define the Forest Land category.

The estimation of deforestation is affected by the definitions of 'forest' versus 'non-forest' area that vary widely in terms of tree size, area, and canopy density. Forest definitions are myriad, however, common to most definitions are threshold parameters including minimum area, minimum height and minimum level of crown cover. In its forest resource assessment of 2005, the FAO[6] uses a minimum cover of 10%, height of 5m and area of 0.5ha. However, the FAO approach of a single worldwide value excludes variability in ecological conditions and differing perceptions of forests.

For the purpose of the Kyoto Protocol[7], it was determined through the Marrakech Accords that Parties should select a single value of crown area, tree height and area to define forests within their national boundaries. Selection must be from within the

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[6] FAO (2006): Global Forest Resources Assessment 2005. Main Report, www.fao.org/forestry/fra2005

[7] UNFCCC (2001): COP-7: The Marrakech accords. (Bonn, Germany: UNFCCC Secretariat) available at http://www.unfccc.int

following ranges, with the understanding that young stands that have not yet reached the necessary cover or height are included as forest:

- ☐ Minimum forest area: 0.05 to 1 ha
- ☐ Potential to reach a minimum height at maturity *in situ* of 2-5 m
- ☐ Minimum tree crown cover (or equivalent stocking level): 10 to 30 %

Under this definition a forest can contain anything from 10% to 100% tree cover; it is only when cover falls below the minimum crown cover as designated by a given country that land is classified as non-forest. However, if this is only a temporary change, such as for timber harvest with regeneration expected, the land remains in the forest classification. The specific definition chosen will have implications on where the boundaries between deforestation and degradation occur.

The Designated National Authority (DNA) in each country is responsible for the forest definition, and a comprehensive and updated list of each country's DNA and their forest definition can be found on http://cdm.unfccc.int/DNA/.

The definition of forests offers some flexibility for countries when designing a monitoring plan because analysis of remote sensing data can adapt to different minimum tree crown cover and minimum forest area thresholds. However, consistency in forest classifications for all REDD activities is critical for integrating different types of information including remote sensing analysis. The use of different definitions impacts the technical earth observation requirements and could influence cost, availability of data, and abilities to integrate and compare data through time.

Deforestation - Most definitions characterize deforestation as the long-term or permanent conversion of land from forest use to other non-forest uses. Under Decision 11/CP.7, the UNFCCC defined deforestation as: "..the direct, human-induced conversion of forested land to non-forested land."

Effectively this definition means a reduction in crown cover from above the threshold for forest definition to below this threshold. For example, if a country defines a forest as having a crown cover greater than 30%, then deforestation would not be recorded until the crown cover was reduced below this limit. Yet other countries may define a forest as one with a crown cover of 20% or even 10% and thus deforestation would not be recorded until the crown cover was reduced below these limits. If forest cover decreases below the threshold only temporarily due to say logging, and the forest is expected to regrow the crown cover to above the threshold, then this decrease is not considered deforestation.

Deforestation causes a change in land cover and in land use. Common changes include: conversion of forests to annual cropland, conversion to perennial plants (oil palm, shrubs), conversion to slash-and-burn (shifting cultivation) lands, and conversion to urban lands or other human infrastructure.

Degradation – Where there are human-induced emissions from forests caused by a decrease in canopy cover that does not qualify as deforestation, it is termed as degradation. Therefore, estimations of degraded areas will be affected by the definition of a "degraded forest", which is not standardized.

The IPCC special report on 'Definitions and Methodological Options to Inventory Emissions from Direct Human-Induced Degradation of Forests and Devegetation of Other Vegetation Types' (2003) presents five different potential definitions for degradation along with their pros and cons. The report suggested the following characterization for degradation:

"A direct, human-induced, long-term loss (persisting for X years or more) or at least Y% of forest carbon stocks [and forest values] since time T and not qualifying as deforestation".

The thresholds for carbon loss and minimum area affected as well as long term need to be specified to operationalize this definition. In terms of changes in carbon stocks, degradation therefore would represent a measurable, sustained, human-induced decrease in canopy cover, with measured cover remaining above the threshold for definition of forest.

However, given the difficulty of negotiating a definition acceptable to all Parties, it is also possible that no specific definition will be agreed on, and that any emission/removal will be reported simply as a decrease of carbon stock in the category "Forest remaining forest".

Given the lack of a clear definition for degradation, or even the lack of any definition, makes it difficult to design a monitoring system. However, some general observations and concepts exist and are presented here to inform the debate. Degradation may present a much broader land cover change than deforestation. In reality, monitoring of degradation will be limited by the technical capacity to sense and record the change in canopy cover because small changes will likely not be apparent unless they produce a systematic pattern in the imagery.

Many activities cause degradation of carbon stocks in forests but not all of them can be monitored well with high certainty, and not all of them need to be monitored using remote sensing data, though being able to use such data would give more confidence to reported emissions from degradation. To develop a monitoring system for degradation, it is first necessary that the causes of degradation be identified and the likely impact on the carbon stocks be assessed.

- Area of forests undergoing selective logging (both legal and illegal) with the presence of gaps, roads, and log decks are likely to be observable in remote sensing imagery, especially the network of roads and log decks. The gaps in the canopy caused by harvesting of trees have been detected in imagery such as Landsat using more sophisticated analytical techniques of frequently collected imagery, and the task is somewhat easier to detect when the logging activity is more intense (i.e. higher number of trees logged; see Section 3.3). A combination of legal logging followed by illegal activities in the same concession is likely to cause more degradation and more change in canopy characteristics, and an increased chance that this could be monitored with Landsat type imagery and interpretation. The reduction in carbon stocks from selective logging can also be estimated without the use satellite imagery, i.e. based on methods given in the IPCC GL-AFOLU for estimating changes in carbon stocks of "forests remaining forests", but it is likely that with this option it will be more difficult to estimate emissions from illegal selective logging.

- Degradation of carbon stocks by forest fires could be more difficult to monitor with existing satellite imagery and little to no data exist on the changes in carbon stocks. Depending on the severity and extent of fires, the impact on the carbon stocks could vary widely. In practically all cases for tropical forests, the cause of fire will be human induced as there are little to no dry electric storms in tropical humid forest areas.

- Degradation by over exploitation for fuel wood or other local uses of wood is often followed by animal grazing that prevents regeneration, a situation more common in drier forest areas. This situation is likely not to be detectable from satellite image interpretation unless the rate of degradation was intense causing larger changes in the canopy.

- Invasion by alien or exotic species into already degraded forests can exacerbate the process as they can reduce natural forest regrowth. Exotic species replacing indigenous species are often more prone to further degradation (natural or anthropogenic) and can generally reproduce more prolifically. Whether the area of this type of degradation could be monitored over time with satellite imagery depends if the invasions cause a marked change in the canopy characteristics.

2.3 General Method for Estimating CO_2 Emissions

To facilitate the use of the IPCC GL-AFOLU and GPG reports side by side with the sourcebook, definitions used in the sourcebook remain consistent with the IPCC Guidelines. In this section we summarize key guidance and definitions from the IPCC Guidelines that frame the more detailed procedures that follow.

The term "Categories" as used in IPCC reports refers to specific sources of emissions/removals of greenhouse gases. For the purposes of this sourcebook, the following categories are considered under the AFOLU sector:

- Forest Land converted to Crop Land, Forest Land converted to Grass Land, Forest Land converted to Settlements, Forest Land converted to Wetlands, and Forest Land converted to Other Land are commonly equated to "deforestation".
- A decrease in carbon stocks of Forest Land remaining Forest Land is commonly equated to "forest degradation".

The IPCC Guidelines refer to two basic inputs with which to calculate greenhouse gas inventories: activity data and emissions factors. "Activity data" refer to the extent of an emission/removal category, and in the case of deforestation and forest degradation refers to the areal extent of those categories, presented in hectares. Henceforth for the purposes of this sourcebook, activity data are referred to as area change data. "Emission factors" refer to emissions/removals of greenhouse gases per unit activity, e.g. tons carbon dioxide emitted per hectare of deforestation. Emissions/removals resulting from land-use conversion are manifested in changes in ecosystem carbon stocks, and for consistency with the IPCC Guidelines, we use units of carbon, specifically metric tons of carbon per hectare ($t\ C\ ha^{-1}$), to express emission factors for deforestation and forest degradation.

2.3.1 Assessing activity data

The IPCC Guidelines describe three different **Approaches** for representing the activity data, or the change in area of different land categories (Table 2.2): Approach 1 identifies the total area for each land category - typically from non-spatial country statistics - but does not provide information on the nature and area of conversions between land uses, i.e. it only provides "net" area changes (i.e. deforestation minus afforestation) and thus is not suitable for REDD. Approach 2 involves tracking of land conversions between categories, resulting in a non-spatially explicit land-use conversion matrix. Approach 3 extends Approach 2 by using spatially explicit land conversion information, derived from sampling or wall-to-wall mapping techniques. Similarly to current requirements under the Kyoto Protocol, it is likely that under a REDD mechanism land use changes will be required to be identifiable and traceable in the future, i.e. it is likely that only Approach 3 can be used for REDD implementation[8].

Table 2.2: A summary of the Approaches that can be used for the activity data.

Approach for activity data: Area change
1. total area for each land use category, but no information on conversions (only net changes)
2. tracking of conversions between land-use categories
3. spatially explicit tracking of land-use conversions

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[8] While both Approaches 2 and 3 give gross-net changes among land categories, only Approach 3 allows to estimate gross-net changes within a category, i.e. to detect a deforestation followed by an afforestation, which is not possible with Approach 2 unless detailed supplementary information is provided.

2.3.2 Assessing emission factors

The emission factors are derived from assessments of the changes in carbon stocks in the various carbon pools of a forest. Carbon stock information can be obtained at different **Tier levels** (Table 2.3) and which one is selected is independent of the Approach selected. Tier 1 uses IPCC default values (i.e. biomass in different forest biomes, carbon fraction etc.); Tier 2 requires some country-specific carbon data (i.e. from field inventories, permanent plots), and Tier 3 highly disaggregated national inventory-type data of carbon stocks in different pools and assessment of any change in pools through repeated measurements or modeling. Moving from Tier 1 to Tier 3 increases the accuracy and precision of the estimates, but also increases the complexity and the costs of monitoring.

Table 2.3: A summary of the Tiers that can be used for the emission factors.

Tiers for emission factors: Change in C stocks
1. IPCC default factors
2. Country specific data for key factors
3. Detailed national inventory of key C stocks, repeated measurements of key stocks through time or modeling

Chapter 3 of this sourcebook provides guidance on how to obtain the activity data, or gross change in forest area, with low uncertainty. Chapter 4 focuses on obtaining data for emission factors and providing guidance on how to produce estimates of carbon stocks of forests with low uncertainty suitable for national assessments.

According to the IPCC, estimates should be accurate and uncertainties should be quantified and reduced as far as practicable. Furthermore, carbon stocks of the key or significant categories and pools should be estimated with the higher tiers (see also chapter 4.2.3). As the reported estimates of reduced emissions will likely be the basis of an accounting procedure (as in the Kyoto Protocol), with the eventual assignment of economic incentives, Tier 3 should be the level to aim for. In the context of REDD, however, the methodological choice will inevitably result from a balance between the requirements of accuracy/precision and the cost of monitoring. It is likely that this balance will be guided by the principle of **conservativeness**, i.e. a tier lower than required could be used – or a carbon pool could be ignored - if it can be demonstrated that the overall estimate of reduced emissions are likely to be underestimated (see also chapter 6.4). Thus, when accuracy and precision of the estimates cannot be achieved, estimates of reduced emissions should *at least* be conservative, i.e. with very low probability to be overestimated.

2.4 Reference Emissions Levels and Benchmark Forest Area Map

The estimate of reductions in emissions from deforestation and degradation requires assessing reference emissions levels against which future emissions can be compared. These reference levels represent the historical emissions from deforestation and forest degradation in “forested land” at a national level.

Credible reference levels of emissions can be established for a REDD system using existing scientific and technical tools, and this is the focus of this sourcebook.

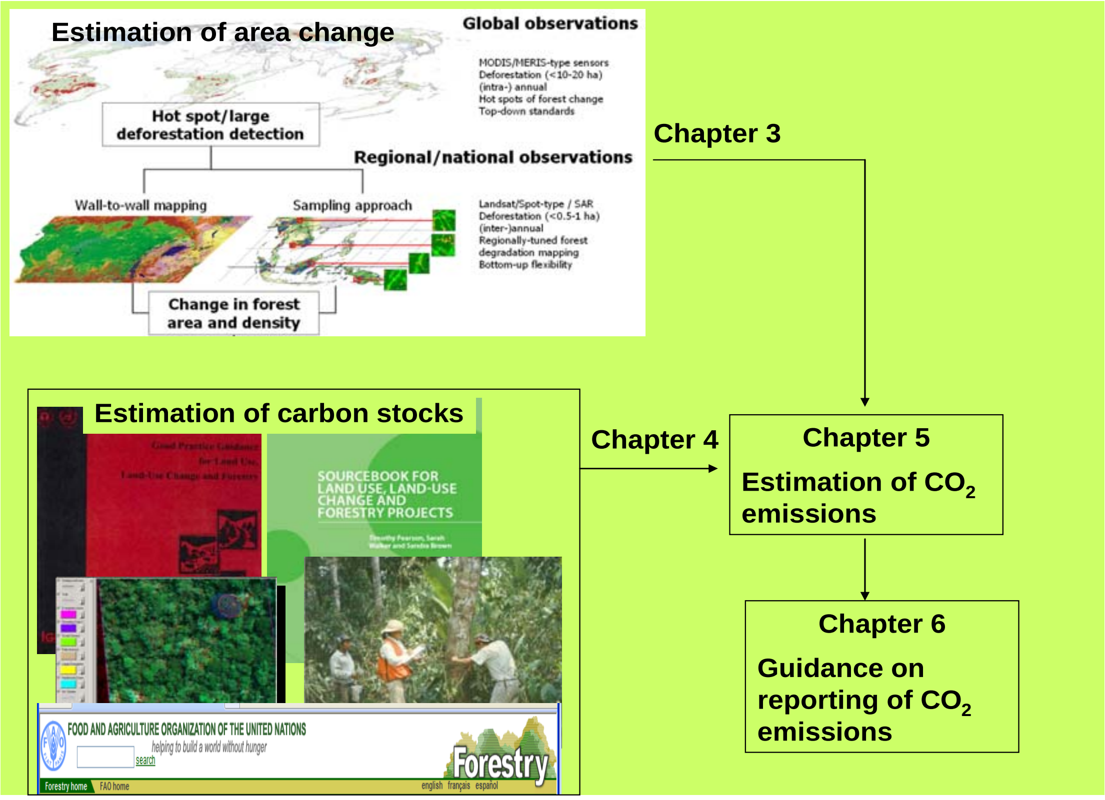
Technically, from remote sensing imagery it is possible to monitor forest area change with confidence from 1990s onwards and estimates of forest C stocks can be obtained from a variety of sources. Feasibility and accuracies will strongly depend on national circumstances (in particular in relation to data availability), that is, potential limitations are more related to resources and data availability than to methodologies.

A related issue is the concept of a **benchmark forest area map**. Any national program to reduce emissions from deforestation and degradation will need to have an initial forest area map to represent the point from which each future forest area assessment will be made and actual changes will be monitored so as to report only gross deforestation going forward. This initial forest area map is referred to here as a benchmark map. This implies that an agreement will be needed by Parties on deciding on a benchmark year against which all future deforestation and degradation will be measured. The use of a benchmark map will clearly show where gross deforestation is occurring, and clearly show where non-forest land is reverting to forests if at some stage in the future this information becomes relevant.

The use of a benchmark map also makes monitoring deforestation (and some degradation) a simpler task. The interpretation of the remote sensing imagery needs to identify only the areas (or pixels) that changed compared to the benchmark map. The benchmark map would then be updated at the start of each new analysis event so that one is just monitoring the loss of forest area from the original benchmark map. The forest area benchmark map would show where forests exist and how they are stratified either for carbon or for other national needs.

2.5 Roadmap for the Sourcebook

The sourcebook is organized as follows:



3 GUIDANCE ON MONITORING OF GROSS CHANGES IN FOREST AREA

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3.1 Scope of chapter

This chapter presents the state of the art for data and approaches to be used for monitoring forest area changes at the national scale in tropical countries using remote sensing imagery. It includes approaches and data for monitoring both deforestation and forest degradation and for establishing historical reference scenarios.

The chapter presents the minimum requirements to develop first order national deforestation databases, using typical and internationally accepted methods. There are more advanced and costly approaches that may lead to more accurate results and would meet the reporting requirements, but they are not presented here.

3.2 Monitoring of Gross Deforestation

3.2.1 General recommendation for establishing a historical reference scenario

As minimum requirement, it is recommended to use Landsat-type remote sensing data (30 m resolution) for years 1990, 2000 and 2005 for monitoring forest cover change with 1 to 5 ha Minimum Mapping Unit (MMU). It might be necessary to use data from a year prior or after 1990, 2000, and 2005 due to availability and cloud contamination. These data will allow assessing gross deforestation (i.e. to derive area deforested for the period considered) and, if desired, producing a map of national forest area (to derive deforestation rates) using a common forest definition. A hybrid approach combining automated digital segmentation and/or classification techniques with visual interpretation and/or validation of the resulting classes/polygons should be preferred as simple, robust and cost effective method.

There may be different spatial units for the detection of forest and of forest change. Remote sensing data analyses become more difficult and more expensive with smaller Minimum Mapping Units (MMU) i.e. more detailed MMU's increase mapping efforts and usually decrease change mapping accuracy. There are several MMU examples from current national and regional remote sensing monitoring systems Brazil PRODES (6,25 ha initially, now 1 ha for digital processing), India national forest monitoring (1 ha), EU-wide CORINE land cover/land use change monitoring (5 ha), 'GMES Service Element' Forest Monitoring (0.5 ha), and Conservation International national case studies (2 ha).

3.2.2 Key features

Presently the only free global mid-resolution (30m) remote sensing imagery are from NASA (Landsat satellites) for around years 1990, 2000, and 2005 (the mid-decadal dataset 2005/2006 is under preparation) with some quality issues in some parts of the tropics (clouds, seasonality, etc). All Landsat data from US archive (USGS) will be available for free from beginning of January 2009

The period 2000-2005 is more representative of recent historical changes and potentially more suitable due to the availability of complimentary data during a recent time frame.

Specifications on minimum requirements for image interpretation are:

- ☐ Geo-location accuracy < 1 pixel, i.e. < 30m,
- ☐ Minimum mapping unit should be between 1 and 5 ha,
- ☐ A consistency assessment should be carried out.

3.2.3 Recommended steps

The following steps are needed for a national assessment that is scientifically credible and can be technically accomplished by in-country experts:

1. Selection of the approach:
    a. Assessment of national circumstances, particularly existing definitions and data sources
    b. Definition of change assessment approach by deciding on:
        i. Satellite imagery
        ii. Sampling versus wall to wall coverage
        iii. Fully visual versus semi-automated interpretation
        iv. Accuracy or consistency assessment
    c. Plan and budget monitoring exercise including:
        i. Hard and Software resources
        ii. Requested Training

2. Implementation of the monitoring system:
    a. Selection of the forest definition
    b. Designation of initial forest area for acquiring satellite data (benchmark map)
    c. Selection and acquisition of the satellite data
    d. Analysis of the satellite data (preprocessing and interpretation)
    e. Assessment of the accuracy

3.2.4 Selection and Implementation of a Monitoring Approach

Step 1: Selection of the forest definition

Currently Annex I Parties use the UNFCCC framework definition of forest and deforestation adopted for implementation of Article 3.3 and 3.4 (see section 2.2) and, without other agreed definition, this definition is considered here as the working definition. Sub-categories of forests (e.g. forest types) can be defined within the framework definition of forest.

Remote sensing imagery allows land cover information only to be obtained. Local expert or field information is needed to derive land use estimates.

Step 2: Designation of initial forest area for acquiring satellite data

Many types of land cover exist within national boundaries. REDD monitoring needs to cover all forest area and the same area needs to be monitored for each reporting period. It is not necessary or practical in many cases to monitor the entire national extent that includes non-forest land cover types. Therefore, a forest mask needs to be designated initially to identify the area to be monitored for each reporting period (referred to in Section 2.2 as the benchmark map).

Ideally, an initial wall-to-wall assessment of the entire national extent would be carried out to identify forested area according to UNFCCC forest definitions at the beginning of the reference period (e.g. to be decided by the Parties to the UNFCCC). This approach may not be practical for large countries. Existing forest maps at appropriate spatial resolution and for a relatively recent time could be used to identify the initial forest extent.

Important principles in identifying the initial forest extent are:

- ☐ The area should include all forest within the national reference boundaries
- ☐ A consistent forest extent should be used for monitoring for future reporting

Step 3: Selection of satellite imagery and coverage

Fundamental requirements of national monitoring systems are that they measure changes throughout all forested area, use consistent methodologies at repeated intervals to obtain accurate results, and verify results with ground-based or very high resolution observations. The only practical approach for such monitoring systems is through interpretation of remotely sensed data supported by ground-based observations. Remote sensing includes data acquired by sensors on board aircraft and space-based platforms. Multiple methods are appropriate and reliable for forest cover monitoring at national scales.

Many data from optical sensors at a variety of resolutions and costs are available for monitoring deforestation (Table 3.1).

Table 3.1: Utility of optical sensors at multiple resolutions for deforestation monitoring

Sensor & resolution	**Examples of current sensors**	**Minimum mapping unit (change)**	**Cost**	**Utility for monitoring**
Coarse (250-1000 m)	SPOT-VGT (1998-) Terra-MODIS (2000-) Envisat-MERIS (2004 -)	~ 100 ha ~ 10-20 ha	Low or free	Consistent pan-tropical annual monitoring to identify large clearings and locate "hotspots" for further analysis with mid resolution
Medium (10-60 m)	Landsat TM or ETM+, Terra-ASTER IRS AWiFs or LISS III CBERS HRCCD DMC SPOT HRV	0.5 - 5 ha	Landsat & CBERS will be free from 2009 $<\$0.001/\text{km}^2$ for historical data $\$0.02/\text{km}^2$ to $\$0.5/\text{km2}$ for recent data	Primary tool to map deforestation and estimate area change
Fine (<5 m)	IKONOS QuickBird Aerial photos	< 0.1 ha	High to very high $\$2\ \text{-}30\ /\text{km}^2$	Validation of results from coarser resolution analysis, and training of algorithms

Availability of medium resolution data

The USA National Aeronautics and Space Administration (NASA) launched a satellite with a mid-resolution sensor that was able to collect land information at a landscape scale. ERTS-1 was launched on July 23, 1972. This satellite, renamed 'Landsat', was the first in a series (seven to date) of Earth-observing satellites that have permitted continuous coverage since 1972. Subsequent satellites have been launched every 2-3 years. Still in operation Landsat 5 and 7 cover the same ground track repeatedly every 16 days.

Almost complete global coverages from these Landsat satellites are available at low or no cost for early 1990s and early 2000s from NASA[9], the USGS[10], or from the University of Maryland's Global Land Cover Facility[11]. These data serve a key role in establishing historical deforestation rates, though in some parts of the humid tropics (e.g. Central Africa) persistent cloudiness is a major limitation to using these data. Until year 2003, Landsat, given its low cost and unrestricted license use, has been the workhorse source for mid-resolution (10-50 m) data analysis.

On April 2003, the Landsat 7 ETM+ scan line corrector failed resulting in data gaps outside of the central portion of acquired images, seriously compromising data quality for land cover monitoring. Given this failure, users would need to explore how the ensuing data gap might be filled at a reasonable cost with alternative sources of data in order to meet the needs for operational decision-making.

Alternative sources of data include Landsat-5, ASTER, SPOT, IRS, CBERS or DMC data (Table 3.2). NASA, in collaboration with USGS, initiated an effort to acquire and compose appropriate imagery to generate a mid-decadal (around years 2005/2006) data set from such alternative sources. The combined Archived Coverage in EROS Archive of the Landsat 5 TM and Landsat-7 ETM+ reprocessed-fill product for the years 2005/2006 covers more than 90% of the land area of the Earth. These data will be processed to a new orthorectifed standard using data from NASA's Shuttle Radar Topography Mission.

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[9] https://zulu.ssc.nasa.gov/mrsid

[10] http://edc.usgs.gov/products/satellite/landsat_ortho.html

[11] http://glcfapp.umiacs.umd.edu/

The USGS is scheduling a no charge Web access to the full Landsat USGS archive[12]. By September 30, 2008 the full Landsat 7 ETM+ archive (since 1999) will become available for ordering at no charge and by January 2009 all archived Landsat 5 TM data (since 1984), Landsat 4 TM (1982-1985) and Landsat 1-5 MSS (1972-1994) will be available for ordering at no charge.

During the selection of the scenes to use in any assessment, seasonality of climate has to be considered: in situations where seasonal forest types (i.e. a distinct dry season where trees may drop their leaves) exist more than one scene should be used. Inter-annual variability has to be considered based on climatic variability.

Table 3.2: Present availability of optical mid-resolution (10-60 m) sensors

Nation	Satellite & sensor	Resolution & coverage	Cost for data acquisition (archive[13])	Feature
USA	Landsat-5 TM	30 m 180×180 km²	600 US$/scene 0.02 US$/km^2 All US archived data will be free from 2009	Images every 16 days to any satellite receiving station. Operating beyond expected lifetime.
USA	Landsat-7 ETM+	30 m 60×180 km²	600 US$/scene 0.06 US$/ km^2 All US archived data will be free from end 2008	On April 2003 the failure of the scan line corrector resulted in data gaps outside of the central portion of images, seriously compromising data quality
USA/ Japan	Terra ASTER	15 m 60×60 km²	60 US$/scene 0.02 US$/km²	Data is acquired on request and is not routinely collected for all areas
India	IRS-P2 LISS-III & AWIFS	23.5 & 56 m		After an experimental phase, AWIFS images can be acquired on a routine basis.
China/ Brazil	CBERS-2 HRCCD	20 m	Free in Brazil	Experimental; Brazil uses on-demand images to bolster their coverage.
Algeria/ China/ Nigeria/ Turkey/ UK	DMC	32 m 160×660 km²	3000 €/scene 0.03 €/km²	Commercial; Brazil uses alongside Landsat data
France	SPOT-5 HRVIR	5-20 m 60×60 km²	2000 €/scene 0.5 €/km²	Commercial Indonesia & Thailand used alongside Landsat data

Optical mid-resolution data have been the primary tool for deforestation monitoring. Other, newer, types of sensors, e.g. Radar (ERS1/2 SAR, JERS-1, ENVISAT-ASAR and ALOS PALSAR) and Lidar, are potentially useful and appropriate. Radar, in particular,

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[12] http://ldcm.usgs.gov/pdf/Landsat_Data_Policy.pdf

[13] Some acquisitions can be programmed (e.g., DMC, SPOT). The cost of programmed data is generally at least twice the cost of archived data. Costs relate to acquisition costs only. They do not include costs for data processing and for data analysis.

alleviates the substantial limitations of optical data in persistently cloudy parts of the tropics. Data from Lidar and Radar have been demonstrated to be useful in project studies, but so far, they are not widely used operationally for tropical deforestation monitoring over large areas. Over the next five years or so, the utility of radar may be enhanced depending on data acquisition, access and scientific developments.

In summary, Landsat-type data around years 1990, 2000 and 2005 will most suitable to assess historical rates and patterns of deforestation.

Utility of coarse resolution data

Coarse resolution (250 m – 1km) data are available from 1998 (SPOT-VGT) or 2000 (MODIS). Although the spatial resolution is coarser than Landsat-type sensors, the temporal resolution is daily, providing the best possibility for cloud-free observations. The higher temporal resolution increases the likelihood of cloud-free images and can augment data sources where persistent cloud cover is problematic. Coarse resolution data also has cost advantages, offers complete spatial coverage, and reduces the amount of data that needs to be processed.

Coarse resolution data cannot be used directly to estimate area of forest change. However, these data are useful for identifying locations of rapid change for further analysis with higher resolution data or as an alert system for controlling deforestation (see section on Brazilian national case study below). For example, MODIS data are used as a stratification tool in combination with medium spatial resolution Landsat data to estimate forest area cleared. The targeted sampling of change reduces the overall resources typically required in assessing change over large nations. In cases where clearings are large and/or change is rapid, visual interpretation can be used to identify where change in forest cover has occurred. Automated methods such as mixture modeling and regression trees (Box 3.1) can also identify changes in tree cover at the sub-pixel level. Validation of analyses with medium and high resolution data in selected locations can be used to assess accuracy. The use of coarse resolution data to identify deforestation hotspots is particularly useful to design a sampling strategy (see following section).

Box 3.1: Mixture models and regression trees

Mixture models estimate the proportion of different land cover components within a pixel. For example, each pixel is described as percentage vegetation, shade, and bare soil components. Components sum to 100%. Image processing software packages often provide mixture models using user-specified values for each end-member (spectral values for pixels that contain 100% of each component). Regression trees are another method to estimate proportions within each component based on training data to calibrate the algorithm. Training data with proportions of each component can be derived from higher resolution data. (see Box 3.5 for more details)

Utility of fine resolution data

Fine resolution (< 5m) data, such as those collected from commercial sensors (e.g., IKONOS, QuickBird) and aircraft, can be prohibitively expensive to cover large areas. However, these data can be used to calibrate algorithms for analyzing medium and high resolution data and to verify the results — that is they can be used as a tool for "ground-truthing" the interpretation of satellite imagery or for assessing the accuracy.

Step 4: Decisions for sampling versus wall to wall coverage

Wall-to-wall (an analysis that covers the full spatial extent of the forested areas) and sampling approaches within the forest mask are both suitable methods for analyzing forest area change.

The main criteria for the selection of wall-to-wall or sampling are:

Wall-to-wall is a common approach if appropriate for national circumstances

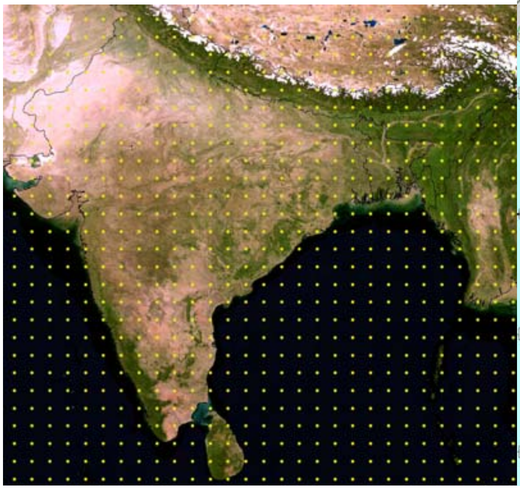
- If resources are not sufficient to complete wall-to wall coverage, sampling is more efficient, in particular for large countries
- Recommended sampling approaches are systematic sampling and stratified sampling (see box 3.2).
- A sampling approach in one reporting period could be extended to wall-to-wall coverage in the subsequent period.

Box 3.2: Systematic and stratified sampling

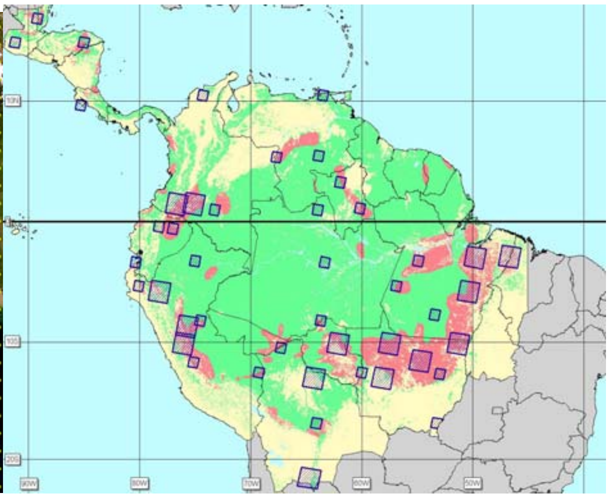
Systematic sampling obtains samples on a regular interval, e.g. one every 10 km.

Sampling efficiency can be improved through spatial stratification (‘stratified sampling’) using known proxy variables (e.g. deforestation hot spots). Proxy variables can be derived from coarse resolution satellite data or by combining other geo-referenced or map information such as distance to roads or settlements, previous deforestation, or factors such as fires.

Example of systematic sampling



Example of stratified sampling



A stratified sampling approach for forest cover change estimation is currently being implemented within the NASA Land Cover and Land Use Change program. This method relies on wall to wall MODIS change indicator maps (at 500 m resolution) to stratify biomes into regions of varying change likelihood. A stratified sample of Landsat-7 ETM+ image pairs is analyzed to quantify biome-wide area of forest clearing. Change estimates can be derived at country level by adapting the sample to the country territory.

A few very large countries, e.g. Brazil and India, have already demonstrated that operational wall to wall systems can be established based on mid-resolution satellite imagery (see section 3.2.5 for details). Brazil has measured deforestation rates in Brazilian Amazonia since the 1980s. These methods could be easily adapted to cope with smaller country sizes. Although a wall-to-wall coverage is ideal, it may not be practical due to large areas and constraints on resources for accurate analysis.

Step 5: Process and analyze the satellite data

Step 5.1: Preprocessing

Satellite imagery usually goes through three main pre-processing steps: geometric corrections are needed to ensure that images in a time series overlay properly, cloud removal is usually the second step in image pre-processing and radiometric corrections are recommended to make change interpretation easier (by ensuring that images have the same spectral values for the same objects).

- ☐ Geometric corrections
    - Low geolocation error of change datasets is to be ensured: average geolocation error (relative between 2 images) should be < 1 pixel
    - Existing Landsat Geocover data usually provide sufficient geometric accuracy and can be used as a baseline; for limited areas Landsat Geocover has geolocation problems
    - Using additional data like non-Geocover Landsat, SPOT, etc. requires effort in manual or automated georectification using ground control points or image to image registration.
- ☐ Cloud and cloud shadow detection and removal
    - Visual interpretation is the preferred method for areas without complete cloud-free satellite coverage,
    - Clouds and cloud shadows to be removed for automated approaches
- ☐ Radiometric corrections
    - Effort needed for radiometric corrections depends on the change assessment approach
    - For simple scene by scene analysis (e.g. visual interpretation), the radiometric effects of topography and atmosphere should be considered in the interpretation process but do not need to be digitally normalized)
    - Sophisticated digital and automated approaches may require radiometric correction to calibrate spectral values to the same reference objects in multitemporal datasets. This is usually done by identifying a water body or dark object and calibrating the other images to the first.
    - Reduction of haze maybe a useful complementary option for digital approaches
    - Topographic normalization is recommended for mountainous environments from a digital terrain model (DTM). For medium resolution data the SRTM (shuttle radar topography mission) DTM can be used with automated approaches[14]

Step 5.2: Analysis methods

Many methods exist to interpret images (Table 3.3). The selection of the method depends on available resources and whether image processing software is available. Whichever method is selected, the results should be repeatable by different analysts.

Visual scene to scene interpretation of forest cover change can be simple and robust, although it is a time-consuming method. A combination of automated methods (segmentation or classification) and visual interpretation can reduce the work load. Automated methods are generally preferable where possible because the interpretation is repeatable and efficient. Even in a fully automated process, visual inspection of the

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[14] E.g. Gallaun H, Schardt M & Linser S (2007) Remote sensing based forest map of Austria and derived environmental indicators. ForestSAT 2007 Conference, Montpellier, France.

result by an analyst familiar with the region should be carried out to ensure appropriate interpretation.

A preliminary visual screening of the image pairs can serve to identify the sample sites where change has occurred between the two dates. This data stratification allows removing the image pairs without change from the processing chain (for the detection and measurement of change).

Changes (for each image pair) can then be measured by comparing the two multi-date final forest maps. The timing of image pairs has to be adjusted to the reference period, e.g. if selected images are dated 1999 and 2006, it would have to be adjusted to 2000-2005.

Visual delineation of land cover entities:

This approach is viable, particularly if image analysis tools and experiences are limited. The visual delineation of land cover entities on printouts (used in former times) is not recommended. On screen delineation should be preferred as producing directly digital results. When land cover entities are delineated visually, they should also be labeled visually.

Table 3.3: Main analysis methods for moderate resolution (~ 30 m) imagery

Method for delineation	Method for class labeling	Practical minimum mapping unit	Principles for use	Advantages / limitations
Dot interpretation (dots sample)	Visual interpretation	< 0.1 ha	- multiple date preferable to single date interpretation - On screen preferable to printouts interpretation	- closest to classical forestry inventories - very accurate although interpreter dependent - no map of changes
Visual delineation (full image)	Visual interpretation	5 – 10 ha	- multiple date analysis preferable - On screen digitizing preferable to delineation on printouts	- easy to implement - time consuming - interpreter dependent
Pixel based classification	Supervised labeling (with training and correction phases)	<1 ha	- selection of common spectral training set from multiple dates / images preferable - filtering needed to avoid noise	- difficult to implement - training phase needed
	Unsupervised clustering + Visual labeling	<1 ha	- interdependent (multiple date) labeling preferable - filtering needed to avoid noise	- difficult to implement - noisy effect without filtering
Object based segmentation	Supervised labeling (with training and correction phases)	1 - 5 ha	- multiple date segmentation preferable - selection of common spectral training set from multiple dates / images preferable	- more reproducible than visual delineation - training phase needed
	Unsupervised clustering + Visual labeling	1 - 5 ha	- multiple date segmentation preferable - interdependent (multiple date) labeling of single date images preferable	- more reproducible than visual delineation

Multi-date image segmentation:

Segmentation for delineating image objects reduces the processing time of image analysis. The delineation provided by this approach is not only more rapid and automatic but also finer than what could be achieved using a manual approach. It is repeatable and therefore more objective than a visual delineation by an analyst. Using multi-date segmentations rather than a pair of individual segmentations is justified by the final objective which is to determine change.

If a segmentation approach is used, the image processing can be ideally decomposed into three steps:

1. Multi-date image segmentation is applied on image pairs: groups of adjacent pixels that show similar land cover change trajectories between the 2 dates are delineated into objects.
2. Objects from every extract (i.e. every date) are classified separately by supervised clustering procedures, leading to two automated forest maps (at date 1 and date 2)
3. Visual interpretation is conducted interdependently on the image pairs to verify/adjust the label the classes and edit possible classification errors.

Image segmentation is the process of partitioning an image into groups of pixels that are spectrally similar and spatially adjacent. Boundaries of pixel groups delineate ground objects in much the same way a human analyst would do based on its shape, tone and texture. However, delineation is more accurate and objective since it is carried out at the pixel level based on quantitative values

Digital classification techniques:

Digital classification applies in the case of automatic delineation.

After segmentation, it is recommended to apply two supervised object classifications separately on the two multi-date images instead of applying a single unsupervised object classification on the image pair because two separate land cover classifications are much easier to produce in an unsupervised step than a direct classification of change trajectories.

The unsupervised object classification should ideally use a common predefined standard training data set of spectral signatures for each type of ecosystem to create initial automated forest maps (at any date and any location within this ecosystem).

General recommendations for image object interpretation methods:

Given the heterogeneity of the forest spectral signatures and the occasionally poor radiometric conditions, the image analysis by a skilled interpreter is indispensable to map land cover and land cover change with high accuracy.

- ❑ Interpretation should focus on change with interdependent assessment of 2 multi-temporal images together.
- ❑ Existing maps may be useful for stratification or helping in the interpretation
- ❑ Scene by scene (i.e. site by site) interpretation is more accurate than interpretation of scene or image mosaics
- ❑ Spectral, spatial and temporal (seasonality) characteristics of the forests have to be considered during the interpretation. In the case of seasonal forests, scenes from the same time of year should be used. Preferably, multiple scenes from different seasons would be used to ensure that changes in forest cover from inter-annual variability in climate are not confused with deforestation.

Step 6: Accuracy assessment

An independent accuracy assessment is an essential component to link area estimates to a crediting system. Reporting accuracy and verification of results are essential components of a monitoring system. Accuracy could be quantified following recommendations of chapter 5 of IPCC Good Practice Guidance 2003.

Accuracies of 80 to 95% are achievable for monitoring with mid-resolution imagery to discriminate between forest and non-forest. Accuracies can be assessed through *in-situ* observations or analysis of very high resolution aircraft or satellite data. In both cases, a statistically valid sampling procedure can be used to determine accuracy.

A detailed description of methods to be used for accuracy assessement is provided in section 3.5 ("Estimating uncertainties in area estimates").

3.2.5 National Case Studies

A. Brazil – annual wall to wall approach

The Brazilian National Space Agency (INPE) produces annual estimates of deforestation in the legal Amazon from a comprehensive annual national monitoring program called PRODES.

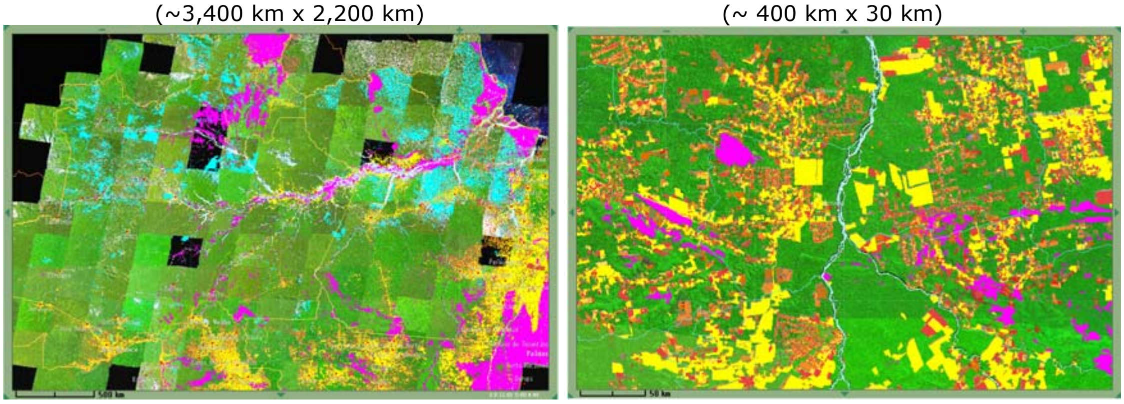
The Brazilian Amazon covers an area of approximately 5 million km2, large enough to cover all of Western Europe. Around 4 million km2 of the Brazilian Amazon is covered by forests. The Government of Brazil decided to generate periodic estimates of the extent and rate of gross deforestation in the Amazon, "a task which could never be conducted without the use of space technology".

The first complete assessment by INPE was undertaken in 1978. Annual assessments have been conducted by INPE since 1988. For each assessment 229 Landsat satellite images are acquired around August and analyzed. Results of the analysis of the satellite imagery are published every year. Spatially-explicit results of the analysis are also publicly available (see http://www.obt.inpe.br/prodes/prodes_1988_2006.htm).

PRODES also provides the spatial distribution of critical areas (in terms of deforestation) in the Amazon. For the period August 1999 to August 2000, more than 80% of the deforestation was concentrated in 49 of the 229 satellite images analyzed.

Box 3.3: Example of result of the PRODES project:

Landsat satellite mosaic of year 2006 with deforestation during period 2000-2006



Brazilian Amazon window
(~3,400 km x 2,200 km)

Zoom on Mato Grosso (around Jurunea)
(~ 400 km x 30 km)

Forested areas appear in green, non-forest areas appear in violet, old deforestation (1997-2000) in yellow and recent deforestation (from 2001) in orange-red.

A new methodological approach based on digital processing is now in operational phase. A geo-referenced, multi-temporal database is produced including a mosaic of deforested areas by States of Brazilian federation. All results for the period 1997 to 2006 are accessible and can be downloaded from the INPE web site at: http://www.dpi.inpe.br/prodesdigital.

Since May 2005, the Brazilian government also has in operation the DETER (Detecção de Desmatamento em Tempo Real) system to serve as an alert in almost real-time (every 15 days) for deforestation events larger than 25 ha. The system uses MODIS data (spatial resolution 250m) and WFI data on board CBERS-2 (spatial resolution 260m) and a combination of linear mixture modeling and visual analysis. Results are publicly available through a web-site: http://www.obt.inpe.br/deter/.

B. India – Biennial wall to wall approach

The application of satellite remote sensing technology to assess the forest cover of the entire country in India began in early 1980s. The National Remote Sensing Agency (NRSA) prepared the first forest map of the country in 1984 at 1:1 million scale by visual interpretation of Landsat data acquired at two periods: 1972-75 and 1980-82. The Forest Survey of India (FSI) has since been assessing the forest cover of the country on a two year cycle. Over the years, there have been improvements both in the remote sensing data and the interpretation techniques. The 10th biennial cycle has just been completed from digital interpretation of data from year 2005 at 23.5 m resolution with a minimum mapping unit of 1 ha. The details of the data, scale of interpretation, methodology followed in wall to wall forest cover mapping over a period of 2 decades done in India is presented in Table 3.4.

The entire assessment from the procurement of satellite data to the reporting, including image rectification, interpretation, ground truthing and validation of the changes by the State/Province Forest Department, takes almost two years.

The last assessment (X cycle) used satellite data from the Indian satellite IRS P6 (Sensor LISS III at 23.5 m resolution) mostly from the period November-December (2004) which is the most suitable period for Indian deciduous forests to be discriminated by satellite data. Satellite imagery with less than 10% cloud cover is selected. For a few cases (e.g. north-east region and Andaman & Nicobar Islands where availability of cloud free data during Nov-Dec is difficult) data from January-February were used.

Table 3.4. State of the Forest Assessments of India

Assessment	Data Period	Satellite Sensor	Resolution	Scale	Analysis	Forest Cover Million ha
I	1981-83	LANDSAT-MSS	80 m	1:1 million	visual	64.08
II	1985-87	LANDSAT-TM	30 m	1:250,000	visual	63.88
III	1987-89	LANDSAT-TM	30 m	1:250,000	Visual	63.94
IV	1989-91	LANDSAT-TM	30 m	1:250,000	Visual	63.94
V	1991-93	IRS-1B LISSII	36.25 m	1:250,000	Visual	63.89
VI	1993-95	IRS-1B LISSII	36.25 m	1:250,000	Visual	63.34
VII	1996-98	IRS-1C/1D LISS III	23.5 m	1:250,000	digital/ visual	63.73
VIII	2000	IRS-1C/1D LISS III	23.5 m	1:50,000	digital	65.38
IX	2002	IRS-1D LISS III	23.5 m	1:50,000	digital	67.78
X	2004	IRS P6- LISS III	23.5 m	1:50,000	digital	67.70

Satellite data are digitally processed, including radiometric and contrast corrections and geometric rectification (using geo-referenced topographic sheets at 1:50,000 scale from Survey of India). The interpretation involves a hybrid approach combining unsupervised classification in raster format and on screen visual interpretation of classes. The Normalized Difference Vegetation Index (NDVI) is used for excluding non-vegetated areas. The areas of less than 1 ha are filtered (removed).

India classifies its lands into the following cover classes:

Very Dense Forest	All lands with tree cover of canopy density of 70% and above
Moderately Dense Forest	All lands with tree cover of canopy density between 40 % and 70 % above
Open Forest	All lands with tree cover of canopy density between 10 – 40 %.
Scrub	All forest lands with poor tree growth mainly of small or stunted trees having canopy density less than 10 percent.
Non-forest	Any area not included in the above classes.

The initial interpretation is then followed by extensive ground verification which takes more than six months. All the necessary corrections are subsequently incorporated. Reference data collected by the interpreter during the field campaigns are used in the classification of the forest cover patches into canopy density classes. District wise and States/Union Territories forest cover maps are produced.

Accuracy assessment is an independent exercise. Randomly selected sample points are verified on the ground (field inventory data) or with satellite data at 5.8 m resolution and compared with interpretation results. In the X assessment, 4,291 points were randomly distributed over the entire country. The overall accuracy level of the assessment has been found to be 92 %

C. Congo basin – example of a sampling approach

Analyses of changes in forest cover at national scales have been carried out by the research community. These studies have advanced methodologies for deforestation monitoring and provided assessments of deforestation outside the realm of national governments. As one example, a test of the systematic sampling approach has been carried out in Central Africa to derive area estimates of forest cover change between 1990 and 2000. The proposed systematic sampling approach using mid-resolution imagery (Landsat) was operationally applied to the entire Congo River basin to accurately estimate deforestation at regional level and, for large-size countries, at national level. The survey was composed of 10 × 10 km2 sampling sites systematically distributed every 0.5° over the whole forest domain of Central Africa, corresponding to a sampling rate of 3.3 % of total area. For each of the 571 sites, subsets were extracted from both Landsat TM and ETM+ imagery acquired in 1990 and 2000 respectively. The satellite imagery was analyzed with object-based (multi-date segmentation) unsupervised classification techniques.

Around 60% of the 390 cloud-free images do not show any forest cover change. For the other 165 sites, the results are represented by a change matrix for every sample site describing four regrouped land cover change processes, e.g. deforestation, reforestation, forest degradation and forest recovery (the samples in which change in forest cover is observed are classified into 10 land cover classes, i.e. “dense forest”, “degraded forest”, “long fallow & secondary forest”, “forest/agriculture mosaic”, “agriculture & short fallow”, “bare soil & urban area”, “non forest vegetation”, “forest-savannah mosaic”, “water bodies” and “no data”). “Degraded forest” were defined spectrally from the imagery (lighter tones in image color composites as compared to dense forests – see next picture).

For a region like Central Africa (with 180 Million ha), using 390 samples, corresponding to a sampling rate of 3.3 %, this exercise estimates the annual deforestation rate at 0.21 ± 0.05 % for the period 1990-2000. For the Democratic Republic of Congo which is covered by a large-enough number of samples (267), the estimated annual deforestation rate was 0.25 ± 0.06%. Degradation rates were also estimated (annual rate: 0.15 ± 0.03 % for the entire basin).

The accuracy of the image interpretation was evaluated from the 25 quality control sample sites. For the forest/non-forest discrimination the accuracy is estimated at 93 % (n = 100) and at 72 % for the 10 land cover classes mapping (n = 120). The overall accuracy of the 2 regrouped change classes, deforestation and reforestation, is estimated at 91 %. The exercise illustrates also that the statistical precision depends on the sampling intensity.

Box 3.4: Example of results of interpretation for a sample in Congo Basin

Landsat image (TM sensor) of year 1990

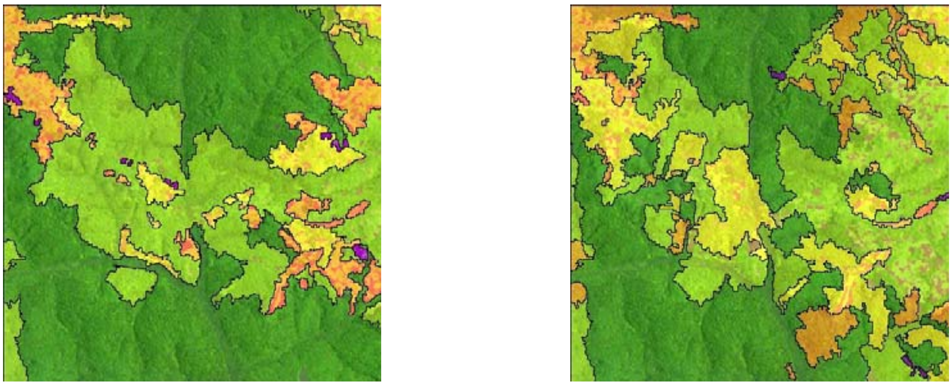
Landsat image (ETM sensor) of year 2000

Box size: 10 km x 10 km

Box size: 10 km x 10 km

Image interpretation of year 1990

Image interpretation of year 2000



Legend: green = Dense forest, light green = degraded forest, yellow = forest/agriculture mosaic, orange = agriculture & fallow.

D. Cameroon – a wall-to-wall approach

A REDD pilot project was initiated in Cameroon under the auspices of the Commission des Forêts d'Afrique Centrale - Central African Forestry Commission- (COMIFAC). This pilot aims at developing a framework for establishing historical references of emissions caused by deforestation, (using Earth Observation for mapping deforestation) combined with regional estimates of degradation nested in the wall-to-wall approach. Preliminary methodological testing in the transition zone between tropical evergreen forest and savannah in Cameroon has been completed[15].

Multi-temporal optical mid-resolution data (Landsat from years 1990 and 2000; DMC from year 2005) was used for the forest mapping in the test area. The method involves a series of three main processing steps: (1) cloud masking, geometric and radiometric adjustment, topographic normalization; (2) forest masking employing a hybrid approach including automatic multi-temporal segmentation, classification and manual correction and (3) land cover classification of the deforested areas based on spectral signature analysis[16].

3.3 Monitoring of Forest Degradation

Many activities cause degradation of carbon stocks in forests but not all of them can be monitored well with high certainty using remote sensing data. As discussed above in Section 2.2, the gaps in the canopy caused by selective harvesting of trees (both legal and illegal) can be detected in imagery such as Landsat using sophisticated analytical techniques of frequently collected imagery, and the task is somewhat easier when the logging activity is more intense (i.e. higher number of trees logged). A combination of legal logging followed by illegal activities in the same concession is likely to cause more degradation and more change in canopy characteristics, and thus an increased chance that this could be monitored with Landsat type imagery and interpretation. The area of forests undergoing selective logging can also be interpreted in remote sensing imagery based on the observations of networks of roads and log decks that are often clearly recognizable in the imagery.

Degradation of carbon stocks by forest fires could be more difficult to monitor with existing satellite imagery

Degradation by over exploitation for fuel wood or other local uses of wood often followed by animal grazing that prevents regeneration, a situation more common in drier forest areas, is likely not to be detectable from satellite image interpretation unless the rate of degradation was intense causing larger changes in the canopy and thus monitoring methods are not presented here.

In this section, two approaches are presented that could be used to monitor selective logging: the direct approach that detects gaps and the indirect approach that detects road networks and log decks. (The timber harvesting practice that fells all the trees, commonly referred to as clear cutting, is not considered to be degradation here—it could be considered as deforestation or forest management practice, depending upon the resulting land use.)

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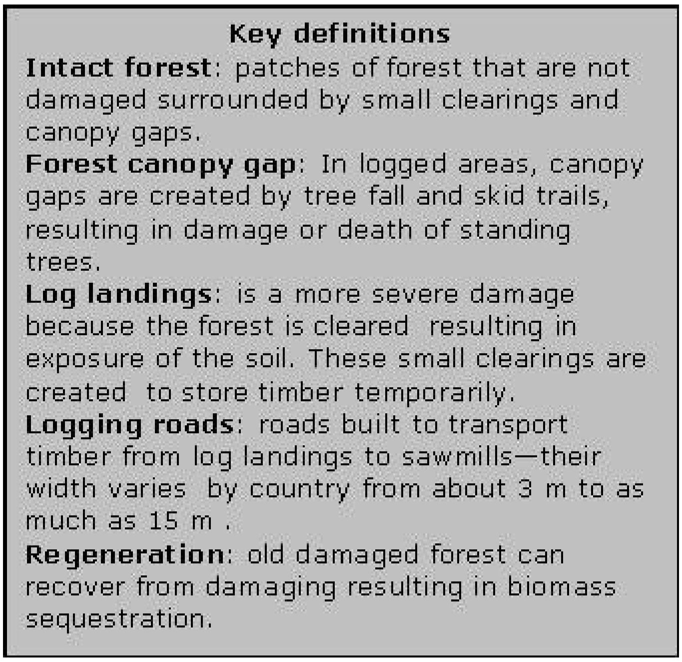
[15] Hirschmugl M, Häusler T, Schardt M, Gomez S & Armathe JA 2008. REDD pilot project in Cameroon - Method development and first results. EaRSeL Conference 2008 Proceedings.

[16] www.gmes-forest.info



Key definitions

Intact forest: patches of forest that are not damaged surrounded by small clearings and canopy gaps.

Forest canopy gap: In logged areas, canopy gaps are created by tree fall and skid trails, resulting in damage or death of standing trees.

Log landings: is a more severe damage because the forest is cleared resulting in exposure of the soil. These small clearings are created to store timber temporarily.

Logging roads: roads built to transport timber from log landings to sawmills—their width varies by country from about 3 m to as much as 15 m .

Regeneration: old damaged forest can recover from damaging resulting in biomass sequestration.

3.3.1 Direct approach to monitor selective logging

Mapping forest degradation with remote sensing data is more challenging than mapping deforestation because the degraded forest is a complex mix of different land cover types (vegetation, dead trees, soil, shade) and the spectral signature of the degradation changes quickly (i.e., < 2 years). High spatial resolution sensors such as Landsat and SPOT have been mostly used so far to address this issue. However, very high resolution satellite imagery, such as Ikonos or Quickbird, and aerial digital image acquired with videography have been used as well. Here, the methods available to detect and map forest degradation caused by selective logging and forest fires – the most predominant types of degradation in tropical regions – using optical sensors only are presented.

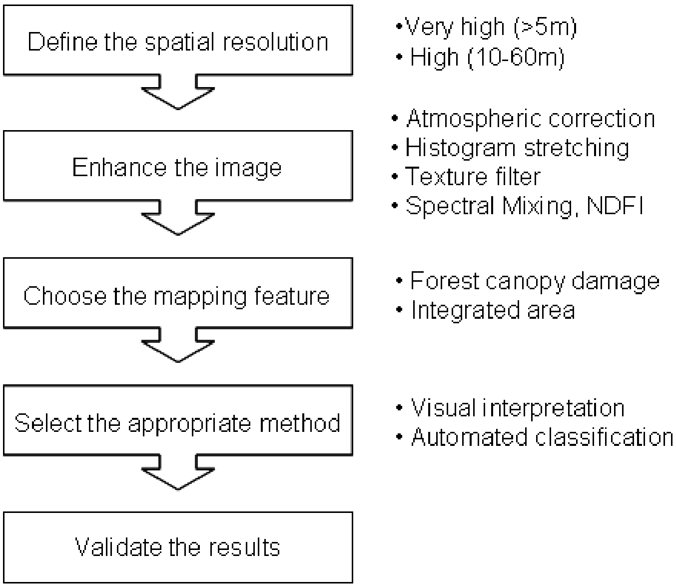
Methods for mapping forest degradation range from simple image interpretation to highly sophisticated automated algorithms. Because the focus is on estimating forest carbon losses associated with degradation, forest canopy gaps and small clearings are the feature of interest to be enhanced and extracted from the satellite imagery. In the case of logging, the damage is associated with areas of tree fall gaps, clearings associated with roads and log landings (i.e., areas cleared to store harvested timber temporarily), and skid trails. The forest canopy gaps and clearings are intermixed with patches of undamaged forests (Figure 3.1).

Figure 3.1: Very high resolution Ikonos image showing common features in selectively logged forests in the Eastern Brazilian Amazon (image size: 11 km x 11 km)

There are two possible methodological approaches to map logged areas: 1) identifying and mapping forest canopy damage (gaps and clearings); or 2) mapping the combined, i.e., integrated, area of forest canopy damage, intact forest and regeneration patches. Estimating the proportion of forest carbon loss in the latter mapping approach is more challenging requiring field sampling measurements of forest canopy damage and extrapolation to the whole integrated area to estimate the damage proportion (see section 4.X).

Mapping forest degradation associated with fires is simpler than that associated with logging because the degraded environment is usually contiguous and more homogeneous than logged areas.

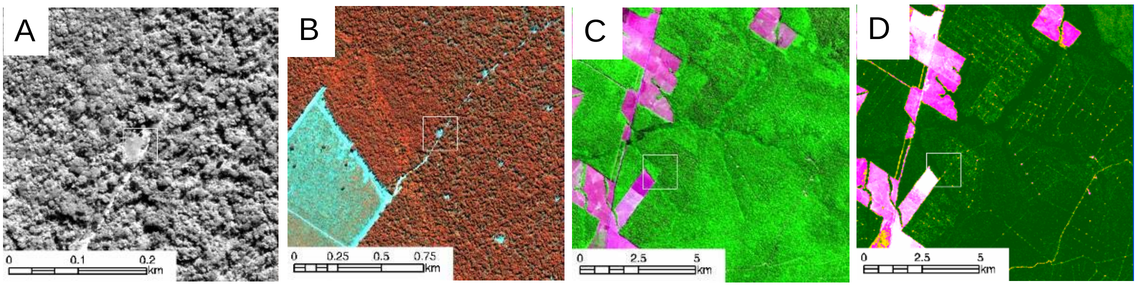
The following chart illustrates the steps needed to map forest degradation:



Step 1: Define the spatial resolution

Defining the appropriate spatial resolution to map forest degradation due to selective logging depends on the type of harvesting operation (managed or unplanned). Managed and non-mechanized logging practiced in a few areas of e.g., the Brazilian Amazon, cannot be detected using spatial resolution in the order of 30-60 m (Figure 3.2) because these type of logging create small forest gaps and little damage to the canopy. Very high resolution imagery, as acquired with orbital and aerial digital videography, is required to directly map forest canopy damage of these types. Unplanned logging generally creates more impact allowing the detection of forest canopy damage at spatial resolution between 30-60 m.

Figure 3.2. Unplanned logged forest in Sinop, Mato Grosso, Brazilian Amazon in: (A) Ikonos panchromatic image (1 meter pixel); (B) Ikonos multi-spectral and panchromatic fusion (4 meter pixel); (C) Landsat TM5 multi-spectral (R5, G4, B3; 30 meter pixel); and (D) Nornalized Difference Fraction Index (NDFI) image (sub-pixel within 30 m). These images were acquired in August 2001.

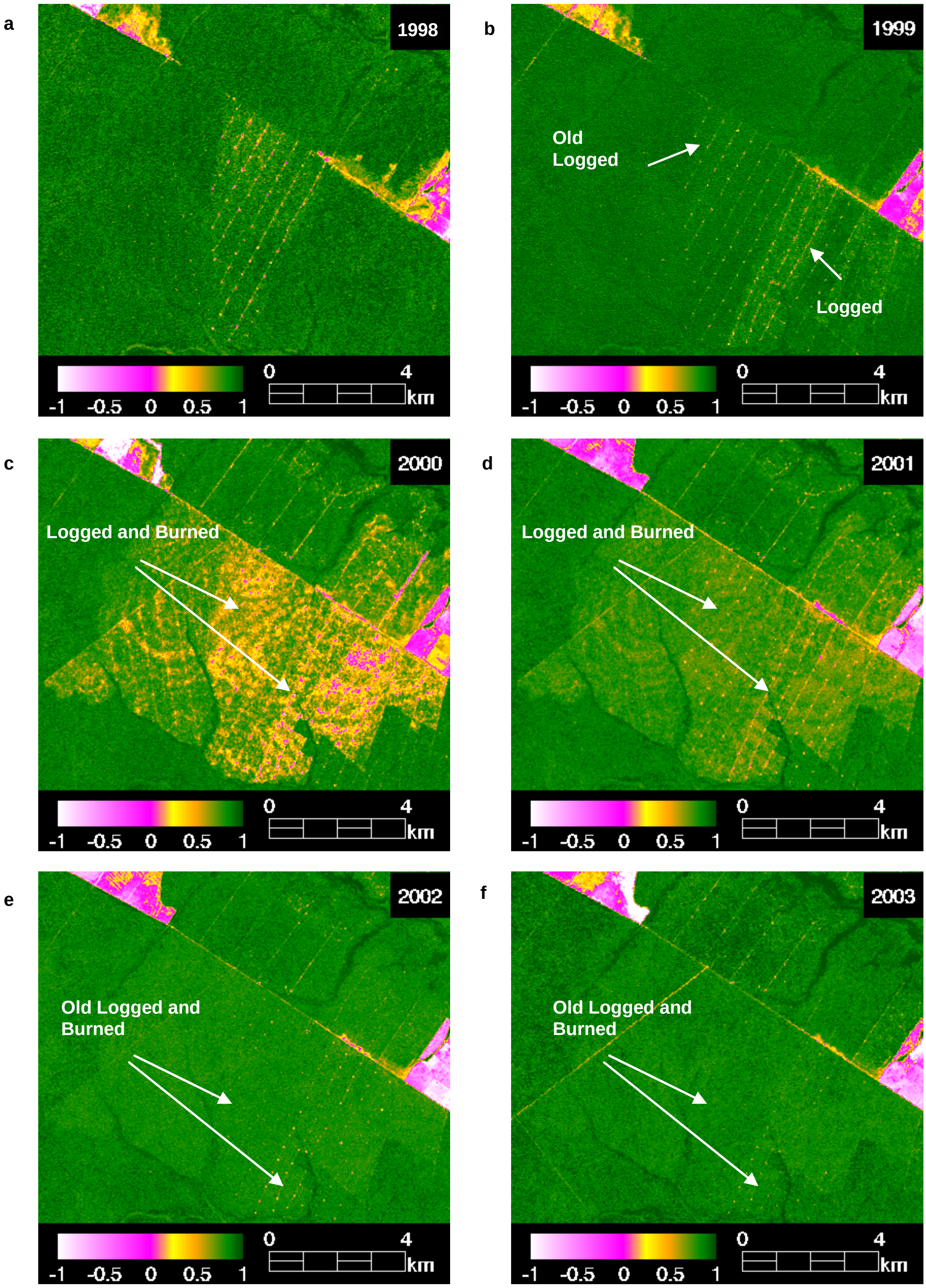


Step 2: Enhance the image

Detecting forest degradation with satellite images usually requires improving the spectral contrast of the degradation signature relative to the background. In tropical forest regions, atmospheric correction and haze removal are recommended techniques to be applied to high resolution images. Histogram stretching improves image color contrast and is a recommended technique. However, at high spatial resolution histogram stretching is not enough to enhance the image to detect forest degradation due to logging. Figure 3.2C shows an example of a color composite of reflectance bands (R5,G4,B3) of Landsat image after a linear stretching with little or no evidence of logging. At fine/moderate spatial resolution, such as the resolution of Landsat and Spot 4 images, a spectral mixed signal of green vegetation (GV), soil, non-photosynthetic vegetation (NPV) and shade is expected within the pixels. That is why the most robust techniques to map selective logging impacts are based on fraction images derived from spectral mixture analysis (SMA). Fractions are sub-pixel estimates of the pure materials (endmembers) expected within pixel sizes such as those of Landsat (i.e., 30 m): GV, soil, NPV and shade endmembers (see SMA Box 1). Figure 3.2D shows the same area and image as Figure 3.2C with logging signature enhanced with the Normalized Difference Fraction Index (NDFI; see Box 3.5). The SMA and NDFI have been successfully applied to Landsat and SPOT images in the Brazilian Amazon to enhance the detection of logging and burned forests (Figure 3.3).

Because the degradation signatures of logging and forest fires change quickly in high resolution imagery (i.e., < one year), annual mapping is required. Figure 3.3 illustrates this problem showing logging and forest fires scars changing every year over the period of 1998 to 2003. This has important implications for monitoring carbon stocks in degraded forests because old degraded forests (i.e., with less carbon stocks) can be misclassified as intact forests. Therefore, annual detection and mapping the canopy damage associated with logging and forest fires is mandatory to monitoring forest degradation with high resolution multispectral imagery such as SPOT and Landsat.

Figure 3.3: Forest degradation annual change due to selective logging and logging and burning in Sinop region, Mato Grosso State, Brazil.



Step 3: Select the mapping feature and methods

Forest canopy damage (gaps and clearings) areas are easier to identify in very high spatial resolution images (Figure 3.2A-B). Image visual interpretation or automated image segmentation can be used to map forest canopy damage areas at this resolution. However, there is a tradeoff between these two methodological approaches when applied to the very high spatial resolution images. Visual identification and delineation of canopy damage and small clearings are more accurate but time consuming, whereas automated segmentation is faster but generates false positive errors that usually require visual auditing and manual correction of these errors. High spatial resolution imagery is the most common type of images used to map logging (unplanned) over large areas. Visual interpretation at this resolution does not allow the interpreter to identify individual gaps and because of this limitation the integrated area – including forest canopy damage, and patches of intact forest and regeneration – is the chosen mapping feature with this approach. Most of the automated techniques – applied at high spatial resolution – map the integrated area as well with only the ones based on image segmentation and change detection able to map directly forest canopy damage. In the case of burned forests, both visual interpretation and automated algorithms can be used and very high and high spatial resolution imagery have been used.

Data Needs

There are several optical sensors that can be used to map forest degradation caused by selective logging and forest fires (Table 3.5). Users might consider the following factors when defining data needs:

- ☐ Degradation intensity—is the logging intensity low or high?
- ☐ Extent of the area for analysis—large or small areal extent?
- ☐ Technique that will be used—visual or automated?

Very high spatial resolution sensors will be required for mapping low intensity degradation. Small areas can be mapped at this resolution as well if cost is not a limiting factor. If degradation intensity is low and area is large, indirect methods are preferred because cost for acquisition of very high resolution imagery may be prohibitive (see section on Indirect Methods to Map Forest Degradation). For very large areas, high spatial resolution sensors produce satisfactory estimates of the area affected by degradation.

Finally, the spectral resolution and quality of the radiometric signal must be taken into account for monitoring forest degradation at high spatial resolution. The estimation of the abundance of the materials (i.e., end-members) found with the forested pixels, through SMA, requires at least four spectral bands placed in spectral regions that contrast the end-members spectral signatures (see Box 3.5).

Table 3.5: Remote sensing methods tested and validated to map forest degradation caused by selective logging and burning in the Brazilian Amazon.

Mapping Approach	**Sensor**	**Spatial Extent**	**Objective**	**Advantages**	**Disadvantages**
Visual Interpretation	Landsat TM5	Local and Brazilian Amazon	Map integrated logging area and canopy damage of burned forest	Does not require sophisticated image processing techniques	Labor intensive for large areas and may be user biased to define the boundaries of the degraded forest.
Detection of Logging Landings + Harvesting Buffer	Landsat TM5 and ETM+	Local	Map integrated logging area	Relatively simple to implement and satisfactorily estimate the area	Harvesting buffers varies across the landscape and does not reproduce the actual shape of the logged area
Decision Tree	SPOT 4	Local	Map forest canopy damage associated with logging and burning	Simple and intuitive binary classification rules, defined automatically based on statistical methods	It has not been tested in very large areas and classification rules may vary across the landscape
Change Detection	Landsat TM5 and ETM+	Local	Map forest canopy damage associated with logging and burning	Enhances forest canopy damaged areas.	Requires two pairs of radiometrically calibrated images and does not separate natural and anthropogenic forest changes
Image Segmentation	Landsat TM5	Local	Map integrated logged area	Relatively simple to implement	It has not been tested in very large areas and segmentation rules may vary across the landscape
Textural Filters	Landsat TM5 and ETM+	Brazilian Amazon	Map forest canopy damage associated	Relatively simple to implement	
CLAS[17]	Landsat TM5 and ETM+	Three states of the Brazilian Amazon (PA, MT and AC)	Map total logging area (canopy damage, clearings and undamaged forest)	Fully automated and standardized to very large areas.	Requires very high computation power, and pairs of images to detect forest change associated with logging. Requires additional image types for atmospheric correction (MODIS)
NDFI+CCA[18]	Landsat TM5 and ETM+	Local	Map forest canopy damage associated with logging and burning	Enhances forest canopy damaged areas.	It has not been tested in very large areas and does not separate logging from burning

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[17] CLAS: Carnegie Landsat Analysis System

[18] NDFI: Normalized Difference Fraction Index; CCA: Contextual Classification Algorithm

Box 3.5: Spectral Mixture Analysis (SMA)

Detection and mapping forest degradation with remotely sensed data is more challenging than mapping forest conversion because the degraded forest is a complex environment with a mixture of different land cover types (i.e., vegetation, dead trees, bark, soil, shade), causing a mixed pixel problem (see Figure 3.3). In degraded forest environments, the reflectance of each pixel can be decomposed into fractions of green vegetation (GV), non-photosynthetic vegetation (NPV; e.g., dead tree and bark), soil and shade through Spectral Mixture Analysis (SMA). The output of SMA models are fraction images of each pure material found within the degraded forest pixel, known as endmembers. Fractions are more intuitive to interpret than the reflectance of mixed pixels (most common signature at high spatial resolution). For example, soil fraction enhances log landings and logging roads; NPV fraction enhances forest damage and the GV fraction is sensitive to canopy gaps.

The SMA model assumes that the image spectra are formed by a linear combination of *n* pure spectra [or endmembers], such that:

$$(1) \qquad R_b = \sum_{i=1}^{n} F_i \cdot R_{i,b} + \varepsilon_b$$

for

$$(2) \qquad \sum_{i=1}^{n} F = 1$$

where R_b is the reflectance in band b, $R_{i,b}$ is the reflectance for endmember i, in band b, F_i the fraction of endmember i, and b is the residual error for each band. The SMA model error is estimated for each image pixel by computing the RMS error, given by:

$$(3) \qquad RMS = \left[n^{-1} \sum_{b=1}^{n} \varepsilon_b \right]^{1/2}$$

The identification of the nature and number of pure spectra (i.e., endmembers), in the image scene is the most important step for a successful application of SMA models. In Landsat TM/ETM+ images the four types of endmembers are expected in degraded forest environments (GV, NPV, Soil and Shade) can be easily identified in the extreme of image bands scatterplots.

The pixels located at the extremes of the data cloud of the Landsat spectral space are candidate endmembers to run SMA. The final endmembers are selected based on the spectral shape and image context (e.g., soil spectra are mostly associated with unpaved roads and NPV with pasture having senesced vegetation) (figure below).

The SMA model results were evaluated as follows: (1) fraction images are evaluated and interpreted in terms of field context and spatial distribution; (2) the histograms of the fraction images are inspected to evaluate with the models produced physically meaningful results (i.e., fractions ranging from zero to 100%). In time-series applications, as required to monitor forest degradation, fraction values must be consistent over time for invariant targets (i.e., that intact forest not subject to phenological changes must have similar values over time). Several image processing software have spectral plotting and SMA functionalities.

Box 3.5: Continuation

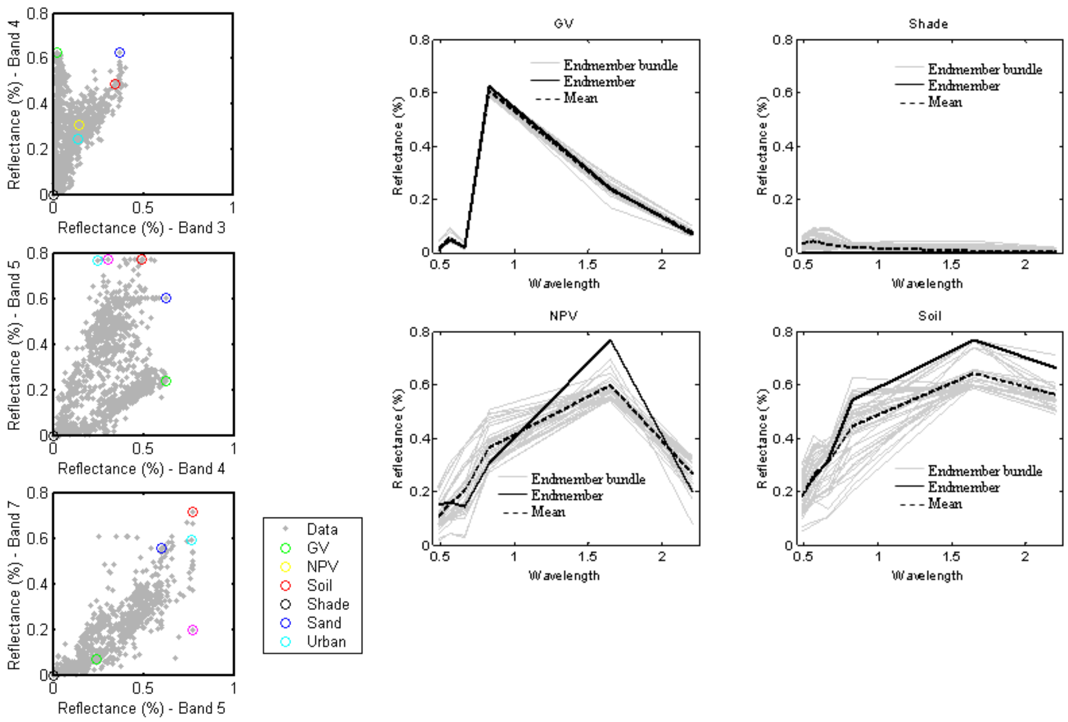


Image scatter-plots of Landsat bands in reflectance space and the spectral curves of GV, Shade, NPV and Soil.

Limitations for forest degradation

There are limiting factors to all methods described above that might be taken into consideration when mapping forest degradation. First, it requires frequent mapping, at least annually, because the spatial signatures of the degraded forests change after one year. Additionally, it is important to keep track of repeated degradation events that affect more drastically the forest structure and composition resulting in greater changes in carbon stocks. Second, the human-caused forest degradation signal can be confused with natural forest changes such as windthrows and phenological changes. Third, all the methods described above are based on optical sensors which are limited by frequent cloud conditions in tropical regions. Finally, higher level of expertise is required to use the most robust automated techniques requiring specialized software and investments in capacity building.

Accuracy assessment

Experience to date on assessing the accuracy of interpretation of selectively logged and burned areas has shown that it is possible to obtain an accuracy ranging from 86 to 95% (Table 3.5). Most studies used conventional accuracy assessment based on error matrix. These studies have used field data and/and or aerial videography imagery as reference data for the accuracy assessment. Another way to assess the accuracy is to report uncertainty by combining different sources of errors (e.g., reflectance retrieval, cloud cover, annualization, manual auditing) to generate the logging map. An example of mapping logging, over a very large area in the Brazilian Amazon, resulted in an uncertainty of 86% for mapping logging using a semi-automated approach. But field inspection, in the same study, showed false-positive and false-negative rates of 5 %.

Progress in application of monitoring systems

Brazil is well-known for its deforestation monitoring systems PRODES (http://www.obt.inpe.br/prodes/). Currently, a new monitoring system is being developed to monitor forest degradation, particularly selective logging, named DETER. The demand for Detex emerged after recent studies confirmed that logging damages annually an area as large as the area affected by deforestation in this region (i.e., 10,000-20,000 km2/year). The DETER system will support the management and monitoring of large forest concession areas in the Brazilian Amazon. All the techniques discussed in this section were developed and validated in the Brazilian Amazon. Recent efforts to export these methodologies to other areas are underway. For example, SMA (Box 3.5) and NDFI (Box 3.6) have being tested in Bolivia with Landsat and Aster imagery. The preliminary results showed that forest canopy damage of low intensity logging, the most common type of logging in the region, could not be detected with Landsat. This corroborates with the findings in the Brazilian Amazon. New sensor data with higher spatial resolution are currently being tested in Bolivia, including Spot 5 (10 m) and Aster (15 m) to evaluate the best sensor for their operational system. Given their higher spatial resolution, Aster and Spot imagery are showing promise for detecting and mapping low intensity logging in Bolivia.

Box 3.6: Calculating Normalized Difference Fraction Index (NDFI)

The detection of logging impacts at moderate spatial resolution is best accomplished at the subpixel scale, with spectral mixture analysis (SMA). Fraction images obtained with SMA can enhance the detection of logging infrastructure and canopy damage. For example, soil fraction can enhance the detection of logging decks and logging roads; NPV fraction enhances damaged and dead vegetation and green vegetation the canopy openings. A new spectral index obtained from fractions derived from SMA, the Normalized Difference Fraction Index (NDFI), enhances even more the degradation signal caused by selective logging. The NDFI is computed by:

$$NDFI = \frac{GV_{Shade} - (NPV + Soil)}{GV_{Shade} + NPV + Soil} \quad (1)$$

where GVshade is the shade-normalized GV fraction given by:

$$GV_{Shade} = \frac{GV}{100 - Shade} \quad (2)$$

The NDFI values range from -1 to 1. For intact forest NDFI values are expected to be high (i.e., about 1) due to the combination of high GVshade (i.e., high GV and canopy Shade) and low NPV and Soil values. As forest becomes degraded, the NPV and Soil fractions are expected to increase, lowering the NDFI values relative to intact forest.

Special software requirements and costs

All the techniques described in this section are available in most remote sensing, commercial and public domain software (refer to the Table that describes image processing software). The software must have the capability to generate GIS vector layers in case image interpretation is chosen, and being able to perform SMA for image enhancement. Image segmentation is the most sophisticated routine required, being available in a few commercial and public domain software packages. Additionally, it is desired that the software allows adding new functions to be added to implement new specialized routines, and have script capability to batch mode processing of large volume of image data.

3.3.2 Indirect approach to monitor forest degradation

Often a direct remote sensing approach to assess forest degradation can not be adopted for various limiting factors (see previous section) which are even more restrictive if forest degradation has to be measured for a historical period and thus observed only with remote sensing data that are already available in the archives.

Moreover the forest definition contained in the UNFCCC framework of provisions (UNFCCC, 2001) does not discriminate between forests with different carbon stocks, and often forest land subcategories defined by countries are based on concepts related to different forest types (e.g. specie compositions) or ecosystems than can be delineated through remote sensing data or through geo-spatial criteria (e.g. altitude). Consequently, any accounting system based on forest definitions that are not containing parameters related to carbon content, will require an extensive and high intensive carbon stock measuring effort (e.g. national forest inventory) in order to report on emissions from forest degradation.

In this context, i.e. the need for activity data (area changes) on degraded forest under the UNFCCC reporting requirement and the lack of remote sensing data for an exhaustive monitoring system, a new methodology has been elaborated with the aim of providing an operational tool that could be applied worldwide. This methodology consists mainly in the adaptation of the concepts and criteria already developed to assess the world's intact forest landscape in the framework of the IPCC Guidance and Guidelines to report GHG emission from forest land. In this new context, the intact forest concept has been used as a proxy to identify forest land without anthropogenic disturbance so as to assess the carbon content present in the forest land:

- intact forests: fully-stocked (any forest with tree cover between 10% and 100% but must be undisturbed, i.e. there has been no timber extraction)
- non-intact forests: not fully-stocked (tree cover must still be higher than 10% to qualify as a forest under the existing UNFCCC rules, but in our definition we assume that in the forest has undergone some level of timber exploitation or canopy degradation).

This distinction should be applied in any forest land use subcategories (forest stratification) that a country is aiming to report under UNFCCC. So for example, if a country is reporting emissions from its forest land using two forest land subcategories, e.g. lowland forest and mountain forest, it should further stratify its territory using the intact approach and in this way it will report on four forest land sub-categories: intact lowland forest; non-intact lowland forest, intact mountain forest and non-intact mountain forest. Thus a country will also have to collect the corresponding carbon pools data in order to characterize each forest land subcategories.

The intact forest areas are defined according to parameters based on spatial criteria that could be applied objectively and systematically over all the country territory. Each country according to its specific national circumstance (e.g. forest practices) may develop its intact forest definition. Here we suggest an intact forest area definition based on the following six criteria:

- Situated within the forest land according to current UNFCCC definitions and with a 1 km buffer zone inside the forest area;
- Larger than 1,000 hectares and with a smallest width of 1 kilometers;
- Containing a contiguous mosaic of natural ecosystems;
- Not fragmented by infrastructure (road, navigable river, pipeline, etc.);
- Without signs of significant human transformation;
- Without burnt lands and young tree sites adjacent to infrastructure objects.

These criteria with larger thresholds for minimum area extension and buffer distance have been used to map intact forest areas globally (www.intactforests.org).

These criteria can be adapted at the country or ecosystem level. For example the minimum extension of an intact forest area or the minimum width can be reduced for mangrove ecosystems. It must be noted that by using these criteria an non- intact forest area would remain non-intact for long time even after the end of human activities, until the signs of human transformation would disappear.

The adoption of the 'intact' concept is also driven by technical and practical reasons. In compliance with current UNFCCC practice it is the Parties' responsibilities to identify forests according to the established 10% - 100% cover range rule. When assessing the condition of such forest areas using satellite remote sensing methodologies, the "negative approach" can be used to discriminate between intact and non-intact forests: disturbance such as the development of roads can be easily detected, whilst the absence of such visual evidence of disturbance can be taken as evidence that what is left is intact. Disturbance is easier to unequivocally identify from satellite imagery than the forest ecosystem characteristics which would need to be determined if we followed the "positive approach" i.e. identifying intact forest and then determining that the rest in non-intact. Following this approach forest conversions between intact forests, non-intact forests and other land uses can be easily measured worldwide through Earth observation satellite imagery; in contrast, any other forest definition (e.g. pristine, virgin, primary/secondary, etc...) is not always measurable.

Method for delineation of intact forest landscapes

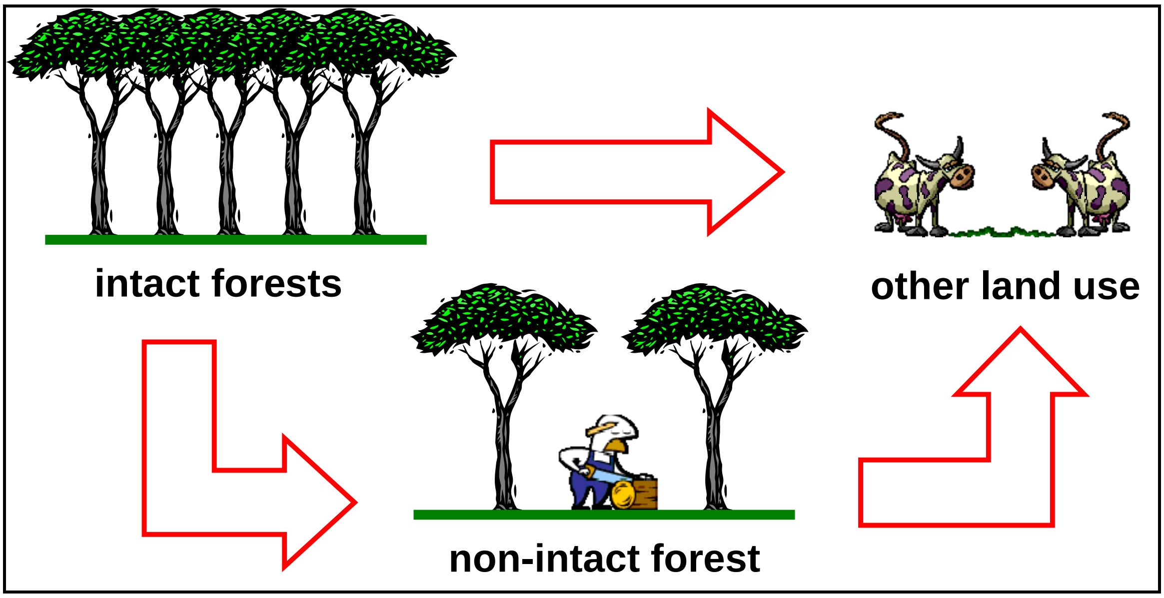
A two-step procedure could be used to exclude non-intact areas and delineate the remaining intact forest:

1. Exclusion of areas around human settlements and infrastructure and residual fragments of landscape smaller than 5,000 ha, based on topographic maps, GIS database, thematic maps, etc. This first step could be done through a spatial analysis tool in a GIS software (this step could be fully automatic in case of good digital database on road networks). The result is a candidate set of landscape fragments whit potential intact forest lands.

2. Further exclusion of non-intact areas and delineation of intact forest lands is done by fine shaping of boundaries, based on visual interpretation methods of high-resolution satellite images (Landsat class data with 15-30 m pixel spatial resolution). Alternatively high-resolution satellite data could be used to develop a more detailed dataset on human infrastructures, that than could be used to delineate intact forest boundaries with a spatial analysis tool of a GIS software.

The distinction between intact and non-intact allows us to account for carbon losses from forest degradation, reporting this as a conversion of intact to non-intact forest. The degradation process is thus accounted for as one of the three potential changes illustrated in Figure 1, i.e. from (i) intact forests to other land use, (ii) non-intact forests to other land use and (iii) intact forests to non-intact forests. In particular carbon emission from forest degradation for each forest type consist of two factors the difference in carbon content between intact and non-intact forests and the area loss of intact forest area during the accounting period. This accounting strategy is fully compatible with the set of rules develop in the IPCC LULUCF Guidance and AFOLU Guidelines for the sections "Forest land remaining Forest land".

Figure 3.4: Forest conversions types considered in the accounting system.



The forest degradation is included in the conversion from intact to non-intact forest, and thus accounted as carbon stock change in that proportion of forest land remaining as forest land.

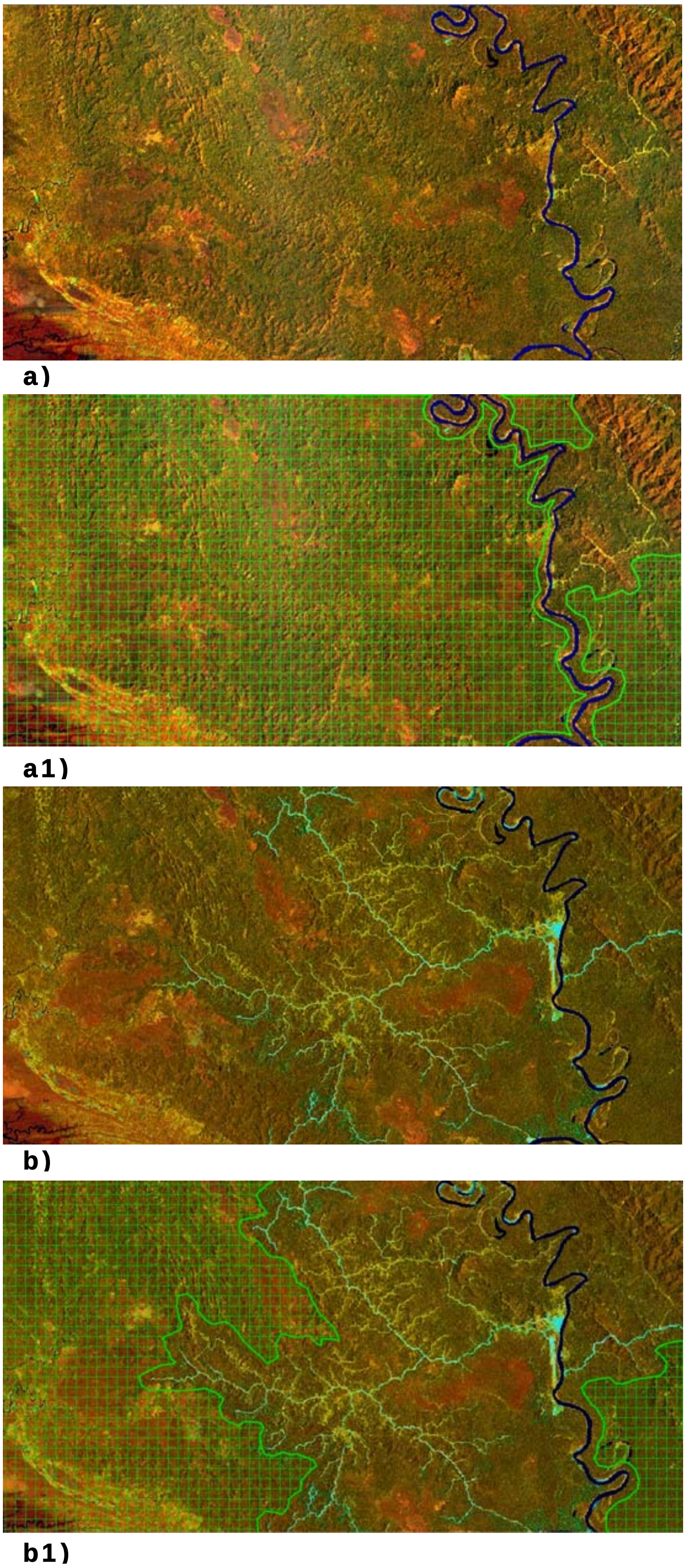


Figure 3.5 Forest degradation assessment in Papua New Guinea

The Landsat satellite images (a) and (b) are representing the same portion of PNG territories in the Gulf Province and they have been acquired respectively in 26.12.1988 and 07.10.2002. In this part of territory it is present only the lowland forest type.

In the image a it is possible to recognize logging roads only on the east side of the river, while in the image b it is possible to recognize a very well developed logging road system also on the west side of the river. The forest canopy (brown-orange-red colours) does not seem to have evident changes in spectral properties (all these images are reflecting the same Landsat band combination 4,5,3).

The images (a1) and (b1) are respectively the same images a and b with some patterned polygons which are representing the extension of the intact forest in the respective dates. In this case an on-screen visual interpretation method have been used to delineate intact forest boundaries.

In order to assess carbon emission from forest degradation for this part of its territory, PNG could report that in 14 years, 51% of the existing intact forest land has been converted in non-intact forest land. Thus the total carbon emission should be equivalent to the intact forest loss multiplied by the carbon content difference between intact and non-intact forest land.

In this particular case, deforestation (road network) is accounting for less than 1%.

Area size: ~ 20km x 10 km

3.4 Systems for observing and mapping fire and burned area

Capabilities to monitor deforestation using medium and coarse resolution imagery exist in only a few countries. Improved efficiency for systematic national monitoring is needed to extend this capability to other countries. Dedicated monitoring of land cover change 'hotspots' of through the detection of fire events using coarse resolution sensors can be cost effective and provide information in near-real time that can be used to trigger further investigation. This section explains what fire information are readily available, potential uses of these data for REDD, and some of the caveats associated with their use. Fires occur for a variety of reasons, including deforestation, wildland fires, and routine maintenance of agricultural land. Mapping fire and burned area from remote sensing can provide information on the locations of fire, but it is often difficult to discern the type of fire. However, the presence of fire in forest can be an indicator that deforestation and/or degradation has occurred.

3.4.1 Satellite-derived fire information

Forest fires occur annually in all vegetation zones and increasing trends in wildland fire activity have been reported in many global regions during the most recent 1-2 decades. There are several observation objectives relating the mapping of the extent and intensity of current ongoing fires (also known as active fires), and the area, severity and impact of burns from post-fire observations. Global observing systems and data products have been developed from various coarse resolution satellite sensor data. There are several polar and geostationary satellite systems with full operational status and some experimental systems providing systematic observations. Additionally, a number of regional and national level monitoring systems exist that utilize near-real-time data acquisition from direct readout receiving stations and include regionally tuned algorithms and customized data delivery and distribution. Table 3.6 lists some major global fire datasets. A more complete list of fire products is available at the GOFC-GOLD Fire Implementation Team website (gofc-fire.umd.edu) and at the Global Fire Monitoring Center (http://www.fire.uni-freiburg.de/).

Polar-orbiting satellites have the advantage of global coverage and typically higher spatial resolution (currently ~ 1km). Multi-year global active fire data records have been generated from the Advanced Very High Resolution Radiometer (AVHRR), the Along-Track Scanning Radiometer (ATSR), and the Moderate Resolution Imaging Spectroradiometer (MODIS). The heritage AVHRR and ATSR sensors were not designed for active fire monitoring and therefore provide less accurate detection; in addition, they do not allow for the estimation of fire intensity (characterized by Fire Radiative Power – FRP). MODIS and the future AVHRR follow-on VIIRS (Visible Infrared Imager Radiometer Suite) have dedicated bands for fire monitoring. These sensors, flown on sun-synchronous satellite platforms provide only a few daily snapshots of fire activity at about the same local time each day. VIRS (Visible and Infrared Scanner) on the sun-asynchronous TRMM (Tropical Rainfall Measuring Mission) satellite covers the entire diurnal cycle over an extended period of time.

Geostationary satellites allow for active fire monitoring at a higher temporal frequency on a hemispheric basis, but typically at coarser spatial resolution (approx 2-4 km). Major active fire products exist based on data from the Geostationary Operational Environmental Satellite (GOES) and METEOSAT Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI). A major international effort is being undertaken by GOFC-GOLD to develop a global system of geostationary fire monitoring that includes a number of additional operational sensors and will provide global coverage.

Several global burned area products exist for specific years and multi-year burned area products are about to be released (MODIS, L3JRC, GLOBCARBON) based on coarse resolution satellite data. The only long term burned area dataset currently available

(GFED2) is partly based on active fire detections. Direct estimation of carbon emissions from these active fire detections or burned area has improved recently, with the use of biogeochemical models, but yet fails to capture fine-scale fire processes due to coarse resolutions. The freely available Landsat archive, combined with compatible data from sensors on other satellite platforms provides an opportunity for more accurate mapping. Active fire products also provide useful complementary information as they capture instantaneous burning at a much smaller scale than burned area products.

Table 3.6: Examples of operational and experimental satellite based observation systems of active fire, burnt areas and associated emissions

Satellite-based fire monitoring	**Information and data access**
Global burnt areas 2000-2007: L3JRC (EC Joint Research Center)	http://www-tem.jrc.it/Disturbance_by_fire/products/burnt_areas/GlobalBurntAreas2000-2007.htm
MODIS active fires and burned areas (University of Maryland /NASA)	http://modis-fire.umd.edu/products.asp
FIRMS: Fire Information for Resource Management System (University of Maryland /NASA/UN FAO)	http://maps.geog.umd.edu/firms
Globcarbon products (ESA)	http://dup.esrin.esa.int/ionia/globcarbon/products.asp
World Fire Atlas (ESA)	http://dup.esrin.esa.int/ionia/wfa/index.asp
Global Fire Emissions Database (GFED2) - multi-year burned area and emissions By NASA	http://ess1.ess.uci.edu/%7Ejranders/data/GFED2/
TRMM VIRS fire product (NASA)	http://daac.gsfc.nasa.gov/precipitation/trmmVirsFire.shtml
Meteosat Second Generation SEVIRI fire monitoring (EUMETSAT)	http://www.eumetsat.int/Home/Main/Access_to_Data/Meteosat_Meteorological_Products/Product_List/index.htm#FIR
Experimental Wildfire Automated Biomass Burning Algorithm: GOES WF-ABBA (University of Wisconsin-Madison / NOAA)	http://cimss.ssec.wisc.edu/goes/burn/wfabba.html

3.4.2 Types of useful fire observations

The use of satellite data for operational monitoring of forest fires has been gaining momentum, but there is still a need for a consistent approach for national level reporting. Pilot activities and systems are however emerging; these include fire early warning systems (pre-fire assessments), notification of active fires and assessments of areas burned.

Pre-fire: fire early warning systems

REDD monitoring focuses on greenhouse gas emissions from forest loss and further has to consider leakage and permanence. For countries with significant amount of forest fires, effective independent early warning systems should be in place to identify areas of potential deforestation and degradation in a timely fashion. A combination of remote sensing and conventional observations allows for the development of early warning systems for prediction of the probability of future fire occurrence and take fire management actions. Such systems can also incorporate socio-economic information (i.e. road networks, management practices) to facilitate the more explicit prediction of ignition.

Table 3.7: Fire observations and their usefulness for national REDD implementation

Approach	Information	REDD objective	Suitability
Pre-fire	early warning system	Protect forest areas at risk and address leakage and permanence	Most suitable for countries with significant amount of wildland fires and known fire regimes
Active fire	Hot spot satellite data	Fire relief and active emissions reduction Support of in-situ actions	Most suitable for countries with large number of small-scale deforestation fires
Post-fire	Burned area estimates	Support estimation of areas of deforestation and degradation	All countries with forest loss due to fire

Active fire

Active fire data from standard products are generally available within 24 hours of satellite overpass. Many systems, based on the processing of direct readout data, provide near-real time information. For example, the Fire Information for Resource Management System (FIRMS), in collaboration with MODIS Rapid Response uses data transmitted by the MODIS instrument on board NASA’s Terra and Aqua satellites. These data are processed to produce maps, images and text files, including ‘fire email alerts’ pertaining to active fire locations to notify protected area, and natural resource managers of fires in their area of interest. Active fires detected using FIRMS, for example, led to the detection of illegal deforestation within protected areas in Belize and Indonesia in 2007.

Caveats of using active fire data

Although active fire data are being used routinely to detect areas of potential degradation and deforestation, it should also be noted that common practice fires (e.g. from agricultural burning) and hotspots from volcanoes and gas flares may also be flagged. To effectively use these fire data to highlight areas that may be at risk, information on land cover and land use are essential. The previous section has already discussed the trade off in temporal and spatial resolution between polar orbiting satellites and geostationary. It is also worth noting that cloud obscures detection of active fires and so in cloudy areas, the number of active fires detected will be underestimated. The accuracy of active fire data has been assessed using coincident medium resolution observations, which enable the estimation of commission and omission rates and detection probabilities as a function of fire characteristics.

Post-fire

Burned area estimates can provide a better understanding of total area affected by fire (as opposed to active fire which provides a snap shot of fires active at the time of overpass). These data can be used to estimate carbon emissions provided a number of data sources are in place; these include current and reliable vegetation and land cover maps, estimates of carbon stocks, and an estimate of fire intensity /burning conditions to estimate fuel combustion (see Canada example in text box).

Burned area products from coarse resolution data are appropriate for global and large-scale assessment. Some natural resource managers also use products, quick look or daily subset images from coarse resolution sensors to get a quick overview of burned area (e.g. MODIS in Kruger National Park, South Africa). For more detailed assessment at the regional scale multi-date Landsat-class data are needed. For the most unequivocal detection pre- and post-burn images should be acquired. Consideration should be given to the timing between images to account for fading of the burned area signal (i.e. due to ash and charcoal removal) and by vegetation re-growth. The infrequent re-visit time of the Landsat-class sensors (typically of the order of several days to 16 days) results in the potential loss of information due to cloud obscuration; in such cases coarse resolution sensors may be useful to fill the gaps.

Burned area maps from Landsat-class sensors have also been used as reference for the validation of coarse resolution products. Reporting of product accuracy is now becoming a standard procedure for all major products, but full global validation is yet to be completed.

Caveats of using burned area data

Low spatial resolution data used for burned area mapping are known to miss smaller burns; as these may be picked up in the active fire detections it is recommended that where possible both active fire and burned area data are used.

3.4.3 Fire observations and national estimation of area change data

Operational fire observations can be integrated in the estimation of activity data for deforestation and forest degradation. As stated above, a number of satellite products are routinely generated for regional to global scale monitoring and available free of charge, while others are still in the development stage. Validation results are becoming available and are typically stratified by region and land cover type. For example, in the Brazilian Amazon, those commission errors for the global MODIS active fire product that are unrelated to previous burning amount to 3% of all fire pixels in areas of deforestation. Omission errors in active fire products depend on the minimum size of fires considered and therefore vary by user needs. Roy and Boschetti (2008) validated the MODIS burned area product over Southern Africa, using a reference dataset of 11 multi-temporal Landsat ETM+ scenes distributed across southern Africa covering approximately 295,000 km^2. The estimated regression line between the proportion of area burned in the MODIS product and in the Landsat data has a slope of 0.75, a near-zero intercept (-0.005) and an r^2 equal to 0.746.

Assuming the deforestation monitoring approach described in section 3.2 of using Landsat-type observations, consistent and continuous active fire and burned area observations can help to guide the related estimations of area change. Coarse-resolution fire related observations are currently not suitable to estimate area loss on a 0,5-1 ha scale but provide high-temporal detail if longer observation periods (i.e. 5-10 years) are used. They provide an additional and independent level of information to build capability and confidence in the national forest monitoring.

Often wildland fires do not result in deforestation but forest degradation. Thus, satellite fire observations can provide a suitable indicator for areas potentially affected by such types of degradation. A national stratification based on fire affected areas could guide more detailed investigations using fine-scale satellite or in situ data to fully quantify degradation area and associated emissions.

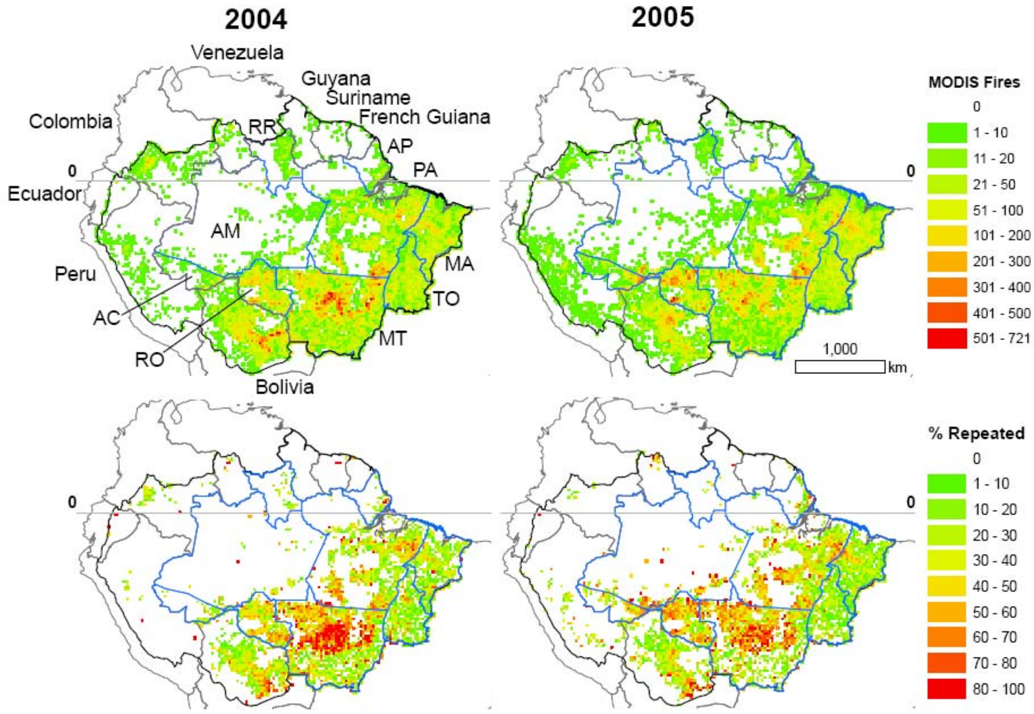
Fire Danger Rating Systems in South-east Asia

Fire Danger Rating Systems (FDRS) were developed for Indonesia and Malaysia to provide early warning of the potential for serious fire and haze events. In particular, they identify time periods when fires can readily start and spread to become uncontrolled fires and time periods when smoke from smouldering fires will cause an unacceptably high level of haze. The FDRS was developed by adapting components of the Canadian Forest Fire Danger Rating System, including the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System, to local vegetation, climate, and fire regime conditions. A smoke potential indicator was developed using the Drought Code (DC) of the FWI System. An ignition potential indicator was developed using the Fine Fuel Moisture Code (FFMC) of the FWI System. The Initial Spread Index (ISI) of the FWI System was used to develop a difficulty of control indicator for grassland fires, a fuel type that can exhibit high rates of spread and fire intensity. This ISI-based indicator was developed using the grass fuel model of the FBP System, along with a standard grass fuel load and curing level estimated from previous Indonesian studies. To provide early warning, the FDRS identifies classes of increasing fire danger as the FFMC, DC, and ISI approach their key threshold values. The Indonesian FDRS is now operated nationally at the Indonesian Meteorological and Geophysical Agency. The Malaysian Meteorological Service operates the Malaysian FDRS and displays regional outputs for the Association of Southeast Asian Nations. The FDRS are being used by forestry, agriculture, environment, and fire and rescue agencies to develop and implement fire prevention, detection, and suppression plans.

Fire monitoring and emissions modeling in the Amazon Basin

Satellite-based detections of actively burning fires have been used as source terms in biomass burning and emissions modeling. Alternative approaches are also emerging for operational monitoring of tropical deforestation. A recent study covering the Amazon Basin shows how the frequency of fire detections might provide complimentary information to enhance existing approaches for real-time deforestation detection (Morton et al., in press). Compared to burning in grasslands, fires for the conversion of forest for agricultural uses were commonly detected at the same location on two or more days per year. In the case of mechanized forest clearing for large-scale crop production, fires were detected on as many as 5-10 days in the same location as farmers piled and burned all stumps, roots, and trunks in preparation for planting soybeans or other crops. In this sense, frequent fires in the same location provide information about the location and timing of new forest clearings and the likely post-clearing land use.

Figure 3.6 Total fire activity in the Amazon, detected by NASA's MODIS instruments, is highest in southeast Bolivia and the Brazilian states of Mato Grosso, Rondônia and Pará during 2004-2005 (Top). Frequent fires in the same location are concentrated in central Mato Grosso (bottom), where peak deforestation for cropland in 2003-2004 led to large increases in fire activity. Credit: Morton et al. (in press), Global Change Biology



Estimating direct carbon emissions from wildland fires in Canada

In support of Canada's National Forest Carbon Monitoring, Accounting and Reporting System, a procedure for estimating direct carbon emissions from wildland fires was developed and tested. Area burned and daily fire spread estimates are derived from satellite products. Spatially and temporally explicit indices of burning conditions for each fire are calculated using fire weather data. The Boreal Fire Effects Model calculates fuel consumption for different live biomass and dead organic matter pools in each burned cell according to fuel type, fuel load, burning conditions, and resulting fire behavior. Carbon emissions are calculated from fuel consumption; other fire emissions are calculated as a proportion of carbon emissions.

3.5 Estimating uncertainties in area estimates

One way of estimating the area of a land category is simply to report the area as indicated on the map derived from remote sensing. While this approach is common, it fails to recognize that maps derived from remote sensing contain errors. There are many factors that contribute to errors in remote sensing maps, and they are discussed below. A suitable approach is to assess the accuracy of the map and use the results of the accuracy assessment to adjust the area estimates. Such an approach accounts for the biases found in the map and allows for improved area estimates.

An accuracy assessment using a sample of higher quality data should be an integral part of any national monitoring and accounting system. If the sample for the higher quality data is statistically rigorous (e.g.: random, stratified, systematic), a calibration estimator (or similar) gives better results than the original survey. Chapter 5 of IPCC Good Practice

Guidance 2003 provides some recommendations and emphasizes that they should be quantified and reduced as far as practicable.

For the case of using remote sensing to derive land change activity data, the accuracy assessment should lead to a quantitative description of the uncertainty of the area for land categories and the associated change in area observed. This may entail category specific thematic accuracy measures, confidence intervals for the area estimates, or an adjustment of the initial area statistics considering known and quantified biases to provide the best estimate. Deriving statistically robust and quantitative assessment of uncertainties is a substantial task and should be an ultimate objective. Any validation should be approached as a process using "best efforts" and "continuous improvement", while working towards a complete and statistically robust uncertainty assessment that may only be achieved in the future.

3.5.1 Sources of error

Different components of the monitoring system affect the quality of the outcomes. They include:

- the quality and suitability of the satellite data (i.e. in terms of spatial, spectral, and temporal resolution),
- the interoperability of different sensors or sensor generations
- the radiometric and geometric preprocessing (i.e. correct geolocation),
- the cartographic and thematic standards (i.e. land category definitions and MMU)
- the interpretation procedure (i.e. classification algorithm or visual interpretation)
- the post-processing of the map products (i.e. dealing with no data values, conversions, integration with different data formats, e.g. vector versus raster), and
- the availability of reference data (e.g. ground truth data) for evaluation and calibration of the system

Given the experiences from a variety of large-scale land cover monitoring systems, many of these error sources can be properly addressed during the monitoring process using widely accepted data and approaches:

- Suitable data characteristics: Landsat-type data, for example, have been proven useful for national-scale land cover and land cover change assessments for MMU's of about 1 ha. Temporal inconsistencies from seasonal variations that may lead to false change (phenology), and different illumination and atmospheric conditions can be reduced in the image selection process by using same-season images or, where available, applying two images for each time step.
- Data quality: Suitable preprocessing quality for most regions is provided by some satellite data provides (i.e. global Landsat Geocover). Geolocation and spectral quality should be checked with available datasets, and related corrections are mandatory when satellite sensors with no or low geometric and radiometric processing levels are used.
- Consistent and transparent mapping: The same cartographic and thematic standards (i. definitions), and accepted interpretation methods should be applied in a transparent manner using expert interpreters to derive the best national estimates. Providing the initial data, intermediate data products, a documentation of all processing steps interpretation keys and training data along with the final maps and estimates supports a transparent consideration

of the monitoring framework applied. Consistent mapping also includes a proper treatment of areas with no data (ie. from constraints due to cloud cover).

Considering the application of suitable satellite data and internationally agreed, consistent and transparent monitoring approaches, the accuracy assessment should focus on providing measures of thematic accuracy.

3.5.2 Accuracy assessment, area estimation of land cover change

Community consensus methods exist for assessing the accuracy of remote sensing-derived (singe-date) land cover maps. The techniques include assessing the accuracy of a map based on independent reference data, and measures such as overall accuracy, errors of omission (error of excluding an area from a category to which it does truly belongs, i.e. area underestimation) and commission (error of including an area in a category to which it does not truly belong, i.e. area overestimation) by land cover class, or errors analyzed by region, and fuzzy accuracy (probability of class membership), all of which may be estimated by statistical sampling.

While the same basic methods used for accuracy assessment of land cover can and should be applied in the context of land cover change, it should be noted that there are additional considerations. It is usually more complicated to obtain suitable, multi-temporal reference data of higher quality to use as the basis of the accuracy assessment; in particular for historical times frames. It is easier to assess land cover change errors of commission by examining areas that are identified as having changed. Because the change classes are often small proportions of landscapes and often concentrated in limited geographic areas, it is hard to assess errors of omission among large area identified as unchanged. Errors in geo-location of multi-temporal datasets, inconsistent processing and analysis, and any inconsistencies in cartographic and thematic standards are exaggerated in change assessments. The lowest quality of available satellite imagery will determine the accuracy of change results. Perhaps, land cover change is ultimately related to the accuracy of forest/non-forest condition at both the beginning and end of satellite data analysis. However, in the case of using two single date maps to derive land cover change, their individual thematic error is multiplicative when used in combination (Fuller et al. 2003). These problems are known and have been address in studies successfully demonstrating accuracy assessments for land cover change (Lowell, 2001, Stehman et al., 2003). It should also be noted, that rather than compare independently produced maps from different dates to find change, it is almost always preferable to combine multiple dates of satellite imagery into a single analysis that identifies change directly. This subtle point is significant, as change is more reliably identified in the multi-date image data than through comparison of maps derived from individual dates of imagery.

3.5.3 Implementation elements for a robust accuracy assessment

For robust accuracy assessment of either land cover or land cover change, there are three principal steps for a statistically rigorous validation: sampling design, response design, and analysis design. An overview of these elements of an accuracy assessment are provided below, and full details of the community consensus “best practices” for these steps are provided in Strahler et al. (2006).

Sample design

The sampling design is a protocol for selecting the locations at which the reference data are obtained. A probability sampling design is the preferred approach and typically combines random or systematic stratified sampling with cluster sampling (depending on the spatial correlation and the cost of the observations). Estimators should be constructed following the principle of consistent estimation, and the sampling strategy should produce accuracy estimators with adequate precision. The design-based sample will define the sample size, sample locations and the reference assessment units (i.e. pixels or image blocks). Stratification should be applied in case of rare classes (i.e. for change categories) and to reflect and account for relevant gradients (i.e. ecoregions) or known factors influencing the accuracy of the mapping process.

Systematic sampling with a random starting point is more efficient than random sampling and is also more traceable. Sampling errors can be quantified with standard statistical formulas, although the estimation is more difficult for systematic sampling. Non-sampling errors (systematic bias) are more difficult to assess and require cross-checking actions (supervision on a sub-sample etc.).

Response design

The response design consists of the protocols used to determine the reference or ground condition label (or labels) and the definition of agreement for comparing the map label(s) to the reference label(s). Reference information should come from data of higher quality, i.e. ground observations or higher-resolution satellite data. Consistency and compatibility in thematic definitions and interpretation is required to compare reference and map data.

Analysis design

The analysis design includes estimation formulas and analysis procedures for accuracy reporting. A suite of statistical estimates are provided from comparing reference and map data. Common approaches are error matrices, class specific accuracies (of commission and omission error), and associated variances and confidence intervals.

3.5.4 Use of Accuracy Assessment Results for Area Estimation

As indicated above, all maps derived from remote sensing include errors, and it is the role of the accuracy assessment to characterize the frequency of errors for each class. Each class may have errors of both omission and commission, and in most situations the errors of omission and commission for a class are not equal. It is possible to use this information on bias in the map to adjust area estimates and also to estimate the uncertainties (confidence intervals) for the areas for each class. Adjusting area estimates on the basis of a rigorous accuracy assessment represents an improvement over simply reporting the areas of classes as indicated in the map. Since areas of land cover change are significant drivers of emissions, providing the best possible estimates of these areas are critical.

A number of methods for using the results of accuracy assessments exist in the literature and from a practical perspective the differences among them are not substantial. One relatively simple yet robust approach is provided by Card (1982). This approach is viable when the accuracy assessment sample design is either random or random stratified. It is relatively easy to use and provides the equations for estimating confidence intervals for the area estimates, a useful explicit characterization of one of the key elements of uncertainty in estimates of GHG emissions.

3.5.5 Considerations for implementation and reporting

The rigorous techniques described in the previous section heavily rely on probability sampling designs and the availability of suitable reference data. Although a national monitoring system has to aim for robust uncertainty estimation, a statistical approach may not be achievable or practicable, in particular for monitoring historical land changes (i.e. deforestation between 1990-2000) or in many developing countries.

In the early stages of developing a national monitoring, the verification efforts should help to build confidence in the approach. Growing experiences (i.e. improving knowledge of source and significance of potential errors), ongoing technical developments, and evolving national capacities will provide continuous improvements and, thus, successively reduce the uncertainty in the land and land change estimates. The monitoring should work backwards from a most recent reference point to use the highest quality data first and allow for progressive improvement in methods. More reference data are usually available for more recent time periods. If no thorough accuracy assessment is possible or practicable, it is recommended to apply the best suitable mapping method in a transparent manner. At a minimum, a consistency assessment should allow some estimation of the quality of the observed land change, i.e. reinterpretation of small samples in an independent manner by regional experts. In this case of lacking reference data for land cover change, validating single date maps usually helps to provide confidence in the change estimates.

Information obtained without a proper statistical sample design can be useful in understanding the basic error structure of the map and help to build confidence in the estimates generated. Such information includes:

- Spatially-distributed confidence values provided by the interpretation or classification algorithms itself. This may include a simple method by withholding a sample of training observations from the classification process and then using those observations as reference data. While the outcome is not free of bias, the outcomes can indicate the relative magnitude of the different kinds of errors likely to be found in the map.
- Systematic qualitative examinations of the map and comparisons (both qualitative and quantitative) with other maps and data sources,
- Systematic review and judgments by local and regional experts,
- Comparisons with non-spatial and statistical data.

Any uncertainty bound should be treated conservatively, in order to avoid a benefit for the country (e.g. an overestimation of sinks or underestimation of emissions) based on highly uncertain data.

For future periods, a statistically robust accuracy assessment should be planned from the start and included in the cost and time budgets. Such an effort would need to be based on a design-based sample, using suitable data of higher quality, and transparent reporting of uncertainties. More detailed and agreed technical guidelines for this purpose can be provided by the technical community.

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4 ESTIMATION OF CARBON STOCKS

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4.1 Overview of carbon stocks, and issues related to C stocks

Monitoring the location and areal extent of deforestation and degradation represents only one of two components involved in assessing emissions from deforestation and degradation. The other component is the emission factors—that is, the changes in carbon stocks of the forests being deforested and degraded that are combined with the activity data for deforestation and degradation for estimating the emissions.

4.1.1 Issues related to carbon stocks

4.1.1.1 The definition of uncertainty for carbon assessments

To estimate the carbon stock on the land one has to sample rather than attempt to measure everything. Sampling is the process by which a subset is studied to allow generalizations to be made about the whole population or area of interest. The values attained from measuring a sample are an estimation of the equivalent value for the entire area or population. Statistics provide us with some idea of how close the estimation is to reality and therefore how certain or uncertain the estimates are.

There are three critical statistical concepts: **bias, accuracy and precision.**

Bias is a systematic distortion often caused by flaws in the measurements or sampling methods.

Accuracy is how close to the actual value your sample measurements are. Accuracy details the agreement between the true value and repeated measured observations or estimations of a quantity.

Precision is how well a value is defined. In sampling, precision illustrates the level of agreement among repeated measurements of the same quantity. This is represented by how closely grouped the results from the various sampling points or plots are.

A popular analogy is a bull’s eye on a target. In this analogy, how tightly the darts are grouped is the precision, how close they are to the center is the accuracy. Below in Figure 4-1 (A), the points are close to the center and are therefore accurate but they are widely spaced and therefore are imprecise. In (B), the points are closely grouped and therefore are precise and could be biased but are far from the center and so are inaccurate. Finally, in (C), the points are close to the center and tightly grouped and are both accurate and precise.

When sampling for carbon, measurements should be accurate (i.e. close to the reality for the entire population) and precise (closely grouped so the results are highly confident or have low uncertainty) so far as it can be judged and so far it is practicable (however, see also Ch. 6.4 on possible approaches for dealing with uncertainties to ensure that REDD values are not over-estimated).

Sampling a subset of the land for carbon estimation involves taking measurements in a number of locations or ‘plots’ that are distributed randomly or systematically over the area to avoid any bias in sampling. The average value when all the plots are combined represents the wider population. A 95 % confidence interval, for example, tells us that 95 times out of a 100 the true carbon density lies within the interval. If the interval is small then the result is precise –it has low uncertainty.

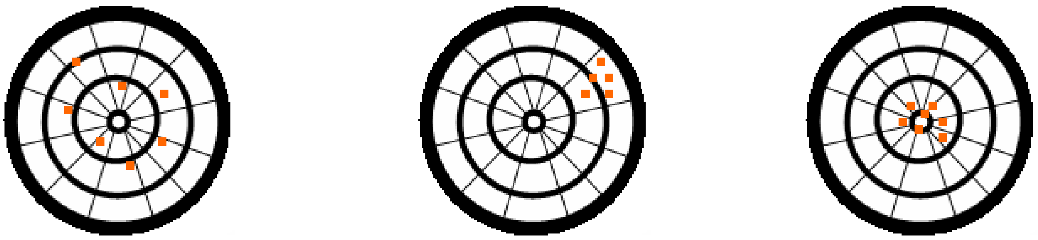

(A) Accurate but not precise (B) Precise but not accurate (C) Accurate and precise

Figure 4.1: Illustration of the concepts of accuracy and precision as they apply to estimates of forest carbon stocks.

4.1.1.2 The importance of "good" carbon stock estimates

In the context of REDD, "good" estimates of carbon stocks means that they have low uncertainty and do not overestimate the true value. A natural preference exists to invest in refined estimates of areas degraded and deforested, then to combine this accurate picture with generalized carbon numbers obtained from default look up tables and literature (e.g. Tier 1 data, see Table 2.2). This is, however, an unsatisfactory strategy because the accuracy of the area estimate will be lost when paired with unsatisfactory carbon data, resulting in poor, uncertain estimates of emissions from deforestation and degradation (see Box 4.1). In reality, the carbon data should be viewed as equally important as the area data, with data of similar quality paired to produce consistent emissions estimates.

Box 4.1: The Importance of Certainty in Carbon Measurements

To be able to determine if real reductions against the reference case have taken place at future monitoring periods, it is important that the uncertainty bounds around the reference case estimate be small. Confidence is generated from the use of good methods that result in accurate and precise estimates of emission reductions. High certainty is required both in the estimates of area change and in the estimates of the emissions arising from the given area of deforestation or degradation, with the emissions based on the carbon stock of the forests being changed.

Much of the focus of REDD is on deriving high quality remotely sensed estimates of area deforested and degraded. The following example shows the importance of an equal focus on both the area change and on the carbon stocks of the forest undergoing change (emissions per unit area).

Remote Sensing Uncertainty	Carbon Stock Uncertainty	Total Uncertainty
5 %	30 %	31%
5 %	20 %	21%
5 %	10 %	11 %

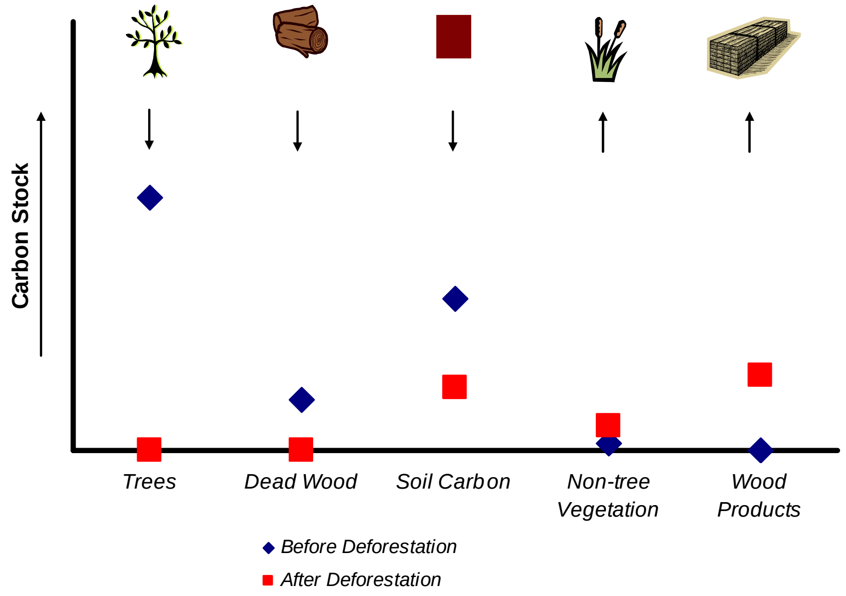
Using the IPCC Tier 1 Simple Propagation of Errors method, despite a constant low uncertainty of 5% for the area change component, the uncertainty of the total final estimate of emissions is governed by the higher uncertainty in the carbon stock data. Therefore if uncertainty is not equally low for the two sources of the ultimate deforestation and degradation emissions, then the investment in the unbalanced half is money poorly spent.

4.1.1.3 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 4.2 below illustrates potential fates of existing forest carbon stocks after deforestation.



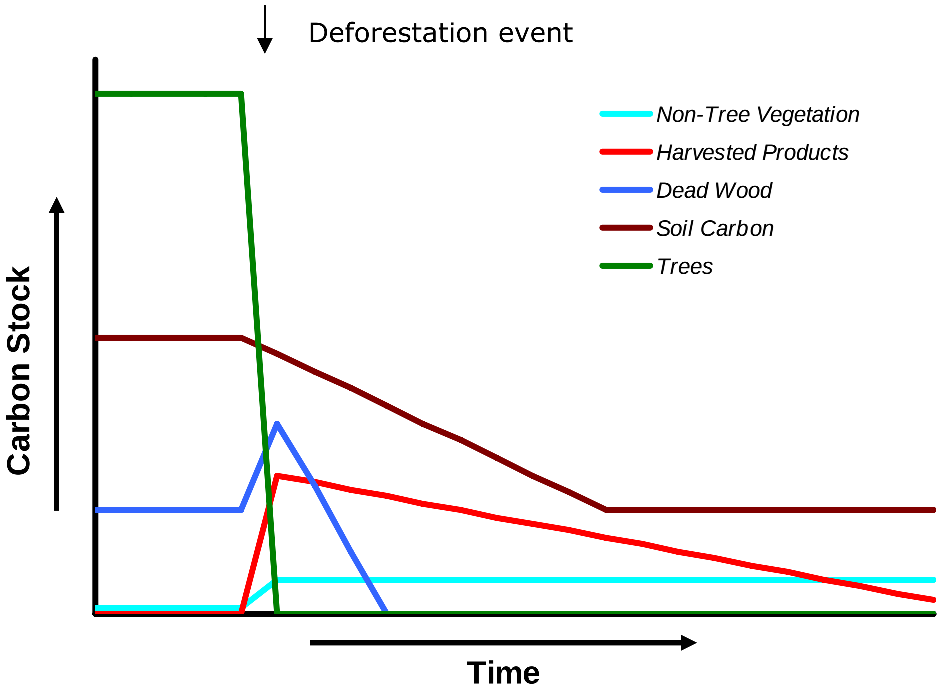


Figure 4.2: Fate of existing forest carbon stocks after deforestation.

4.1.1.4 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 a different stock than a woodland or a mangrove forest. 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. Therefore stratifying forests can lead to more accurate and cost effective emission estimates associated with a given area of deforestation or degradation (see more on this topic below in section 4.3).

4.1.2 Overview of Chapter

In **Section 4.2** 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 4.3** the focus is on: Stratification by Carbon Stock. As discussed in 4.1.1 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 4.4** guidance is given on the actual Estimation of Carbon Stocks of Forests Undergoing Change. Steps are given on how to devise and implement an inventory.

In **Section 4.5** guidance is presented on assessing the Uncertainty resulting from the forest carbon stock estimations.

4.2 Which Tier should be used?

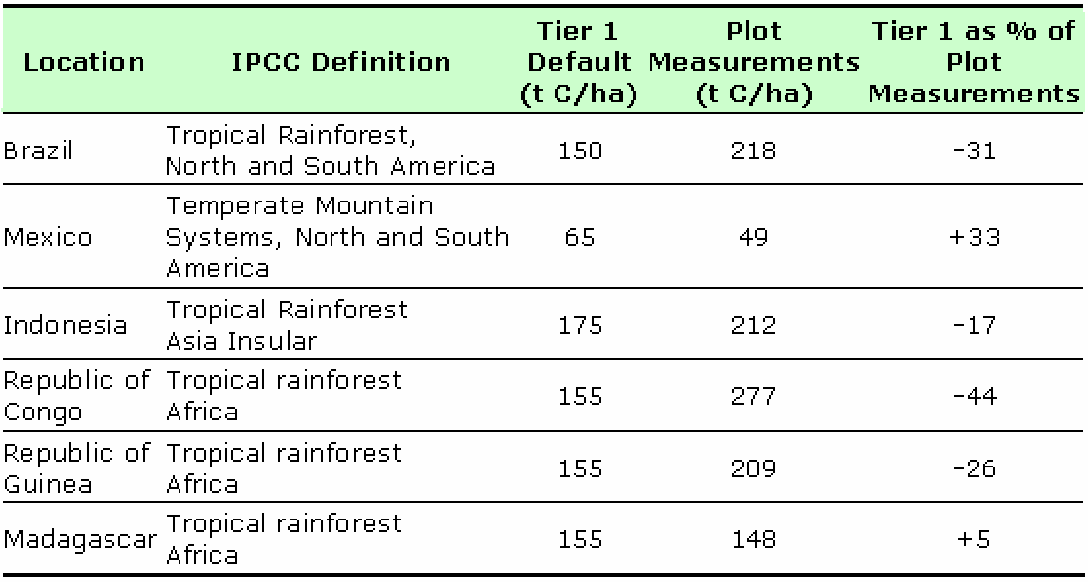
4.2.1 Explanation of IPCC Tiers

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 4.2). 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 4.3). Tier 1 also uses simplified assumptions to calculate 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 Ch 5) 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 4.2– Error in Carbon Stocks from Tier 1 Reporting

To illustrate the error in applying Tier 1 carbon stocks for the carbon element of REDD reporting, 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 plot measurements.



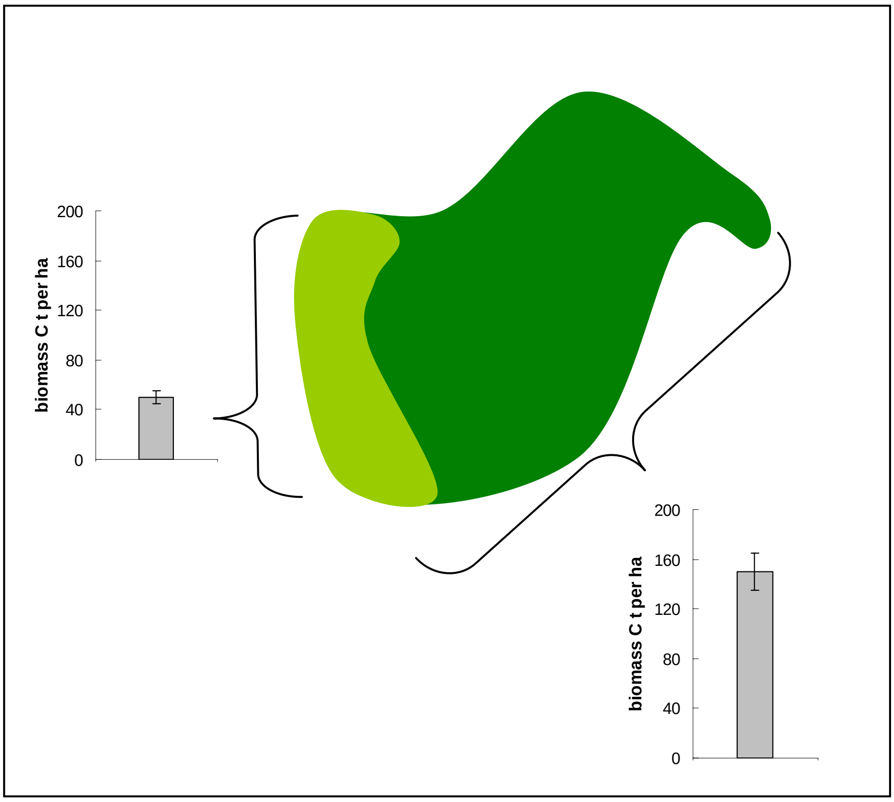
Location	IPCC Definition	Tier 1 Default (t C/ha)	Plot Measurements (t C/ha)	Tier 1 as % of Plot Measurements
Brazil	Tropical Rainforest, North and South America	150	218	-31
Mexico	Temperate Mountain Systems, North and South America	65	49	+33
Indonesia	Tropical Rainforest Asia Insular	175	212	-17
Republic 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 4.3 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 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 4.3 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 4.3: 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 inventories with repeated measures of permanent plots to directly measure changes in forest biomass and/or uses well parameterized models in combination with plot data. Tier 3 often focuses on measurements of trees only, and uses region/forest specific default data and modeling for the other pools. The Tier 3 approach requires long-term commitments of resources and personnel, generally involving the establishment of a permanent organization to house the program (e.g. Box 4.3; Australian Greenhouse Gas Office, USDA Forest Service Forest Inventory and Analysis program). 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 modeling 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, Tier 3 uses the stock difference approach where change in forest biomass stocks is directly estimated from repeated measures or models.

Box 4.3. National forest inventory approach—India as a case study

Traditionally, forest inventories in several countries have been done to obtain a reliable estimate of the forest area and growing stock of wood for overall yield regulation purpose. The information was used to prepare management plans for utilization and development of the forest resource and also to formulate forest policies. The forest inventory provides data of the growing stock wood volume and number of tree per unit area by tree diameter classes and by species composition. Repeated measurement of permanent sample plots also provides the changes in the forest growing stock.

In the developing region of the world, several countries have undertaken an inventory of their forests, usually at the sub-national level but some at the national level. There are, however, a few developing countries like India and China that are conducting a national forest inventory on a regular basis.

Previous Methodology

In India, an inventory at relatively large area basis (about 22.8 million ha of forest in total) using statistically robust approach started in 1965 when the Pre-Investment Survey of Forest Resources (PIS) was launched in the country with FAO/UNDP assistance. The inventory and assessment of the forest resources in the selected areas of the country was continued until 1981. The PIS was then re-organized as Forest Survey India (FSI), a national organization for undertaking national forest inventory and wood consumption studies of the country regularly. After the creation of the FSI, the field inventory continued with the same strength and pace as the PIS but the design was modified. The total area inventoried until the year 2000 was about 69.2 million ha, which includes some areas which were inventoried twice. Thus more than 80% forest area of the country was inventoried comprehensively during a period of 35 years. Systematic sampling has been the basic design under which forest area was divided into grids of equal size (2½´ by 2½´) on topographic sheets and two sample plots were laid in each grid. The intensity of sampling followed in the inventory has been generally 0.01% and sample plot size 0.1 ha.

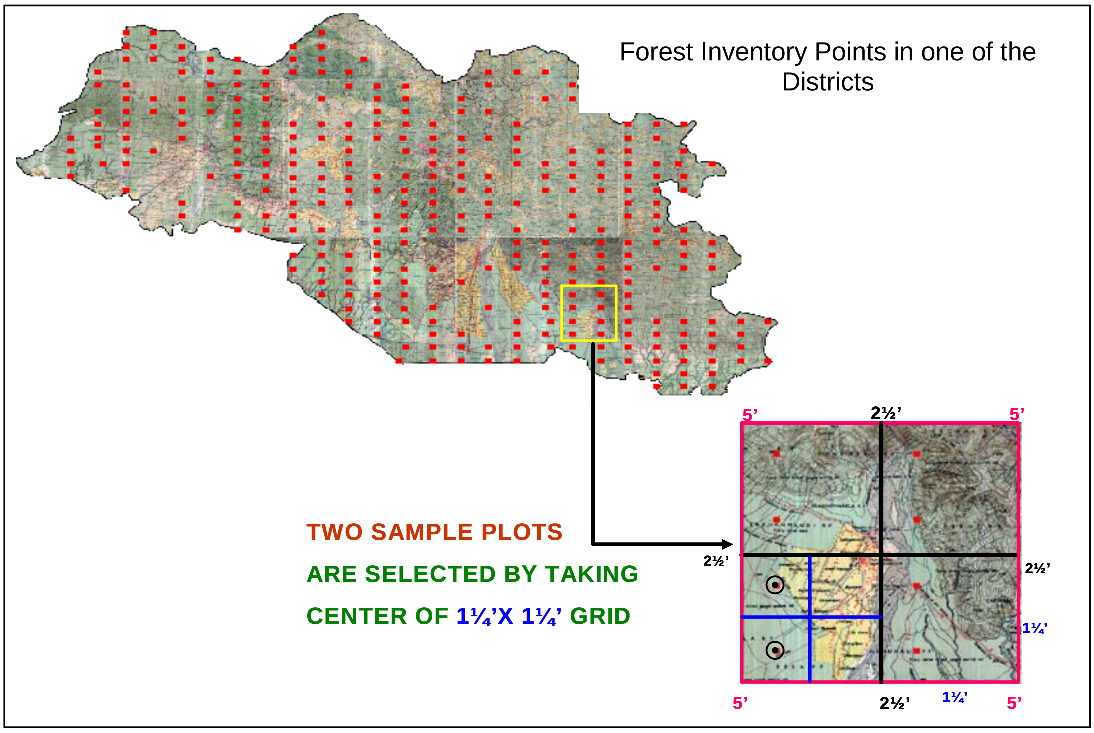
Current Methodology

With a view to generate a national level estimate of growing stock in a short time and coincident with the biennial forest cover assessment based on satellite imagery, a new National Forest Inventory (NFI) was designed in 2001. Under this programme, the country has been divided into 14 physiographic zones based on physiographic features such as climate, soil and vegetation.

The method involved sampling 10 percent of the about 600 civil districts representing the 14 different zones with probability set proportional to district size. About 60 districts were selected to be inventoried in two years period. The first estimate of the growing stock was generated at the zonal and national level based on the inventory of 60 districts covered in the first cycle. These estimates are to be further improved in the second and subsequent cycles as the data of first cycle will be combined with second and subsequent cycles. The random selection of the districts is without replacement; hence each time new districts are selected.

Field Inventory

In the selected districts, all those areas indicated as Reserved Forests, Protected forests, thick jungle, thick forest etc, and any other area reported to be a forest area by the local Divisional Forest Officers (generally un-classed forests) are treated as forest. For each selected district, Survey of India topographic sheets of 1:50,000 scale are divided into 36 grids of 2½´ by 2½´. Further, each grid is divided into 4 sub-grids of 1¼´ by 1¼´ forming the basic sampling frame. Two of these sub-grids are then randomly selected for establishing sample plots. The intersection of diagonals of such sub-grids is marked as the center of the plot at which a square sample plot of 0.1 ha area is laid out to conduct field inventory (see figure below for details).


Forest Inventory Points in one of the Districts

Diameter at breast height (1.37 m) of all the trees above 10 cm (DBH) in the sample plot and height of trees standing in only one quarter of the sample plot are measured. In addition legal status, land use, forest stratum, topography, crop composition, bamboo, regeneration, biotic pressure, species name falling in forest area are also recorded. Two sub plots of 1 m2 are laid out at the opposite corners of the sample plot to collect sample for litter/ humus and soil carbon (from a pit of 30 cm x 30cm x 30cm). Further, nested quadrates of 3mx 3 m and 1mx1 m are laid at 30 m distance from the center of the plot in all the four corners for enumeration of shrubs and herbs to assess the biodiversity.

Costs

The total number of temporary sample plots laid out in the forests of 60 districts is about 8,000 where measurements are completed in two years. The field inventory and the data entry are conducted by the zonal offices of the Forest Survey of India located in four different zones of the country. The data checking and its processing are carried out in FSI headquarters (Dehradun). The estimated cost of inventory and data processing of a sample plot is about US$ 200 of which about US$110 is spent on travel to sample plot, field measurement including checking by supervisors and the rest on field preparation, equipment, designing, data entry, processing etc.

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 though not as precise as repeated measures using permanent plots that can focus directly on stock change and increment, Tier 2 does not require the sustained institutional backing.

4.2.2 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 forest inventory is in place (i.e. most developing countries). Data needs for each Tier are summarized in Table 4.1.

Table 4.1: 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—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 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 permanent 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

4.2.3 Selection of Tier

Tiers should be selected on the basis of goals (e.g. precise measure 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 of emissions/removals, the IPCC Guidelines provide guidance on the identification of "Key Categories". Key categories are sources 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. Key categories can be further broken down to identify significant sub-categories or pools (e.g. above-ground biomass, below-ground biomass, litter, and dead wood) that constitute > 25-30 % emissions/removals for the category.

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 the reference period and for future monitoring of 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 to mid term.

On the other hand, Tier 1 will not deliver the accurate and precise measures needed for key categories/pools by any mechanism in which economic incentives are foreseen. However, the principle of conservatism will likely represent a fundamental parameter to evaluate 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 chapter 6.4).

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 25% of emissions from deforestation, the Tier 1 approach using default transfers and decomposition rates is justified for application to that pool.

4.3 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 vegetation carbon stock for the calculation of emissions.

4.3.1 Why stratify?

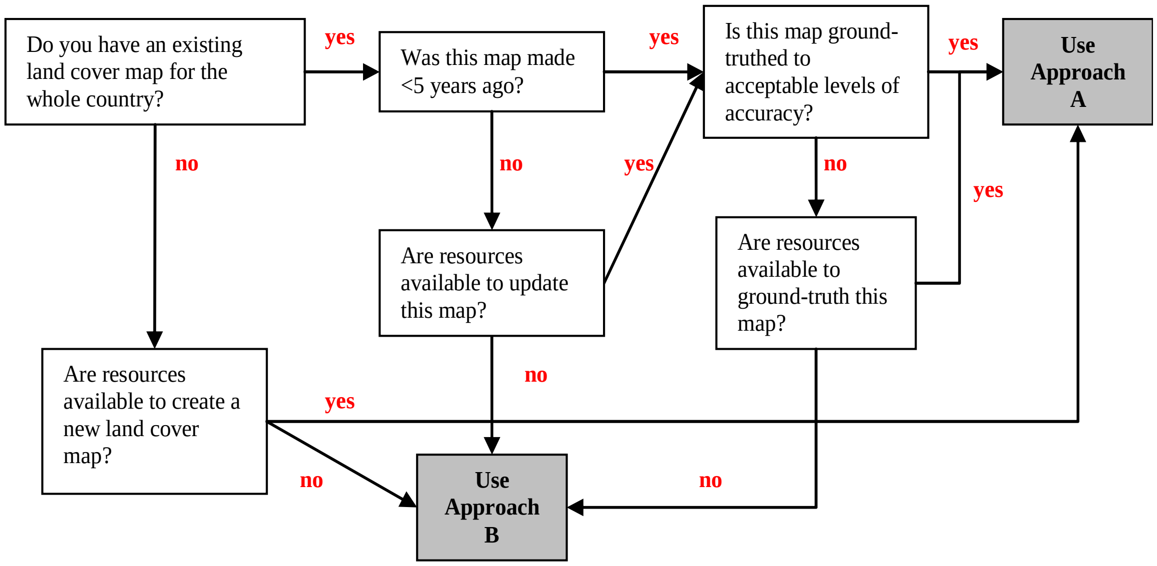
Different carbon stocks exist in different forest types and ecoregions depending on physical factors (e.g., precipitation regime, temperature, soil type, topography), biological factors (tree species composition, stand age, stand density) and anthropogenic factors (disturbance history, logging intensity). 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 emissions. 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 for the specific areas that were deforested or degraded, 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 reductions 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.

4.3.2 Approaches to stratification

There are two different 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 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 preestimated carbon stock values. 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 areas 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 4.4 that provides a decision tree that can be used to select which stratification approach to use. Details of each approach are outlined below.

BOX 4.4: 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 Chapter 2.4).

- 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 (cf. Chapter 3).

- 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 Chapter 3.

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, which would not be valuable for 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 4.5 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.

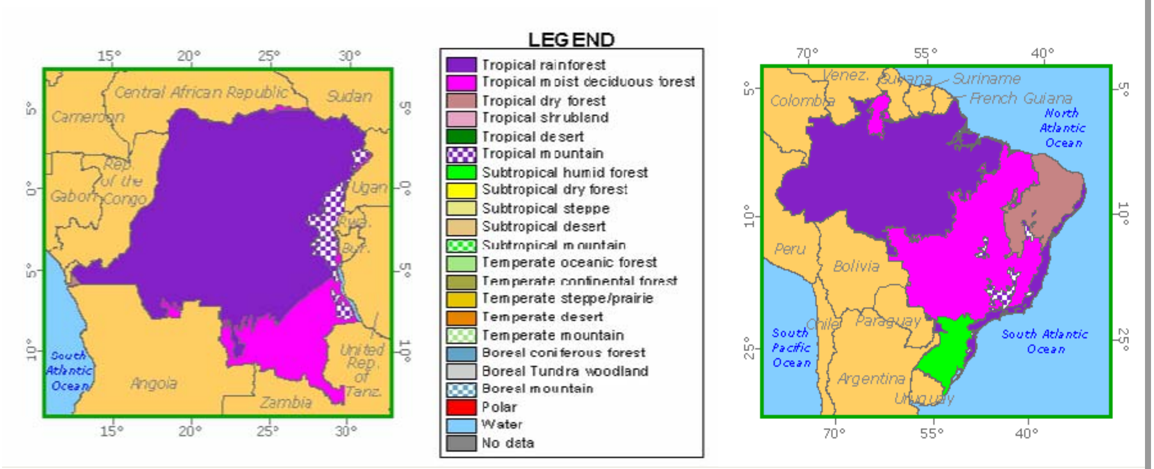
Once strata are delineated on a ground-validated land cover map and forest types have been identified, carbon stocks are estimated for each stratum using appropriate measuring and monitoring methods. A national map of carbon stocks can then be created (cf Section 4.4).

Box 4.5: 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 (roads, rivers)
Forest Age (if known)	Rural population density
Areas of protected forest	

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 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 10-20 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.

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 4.6.

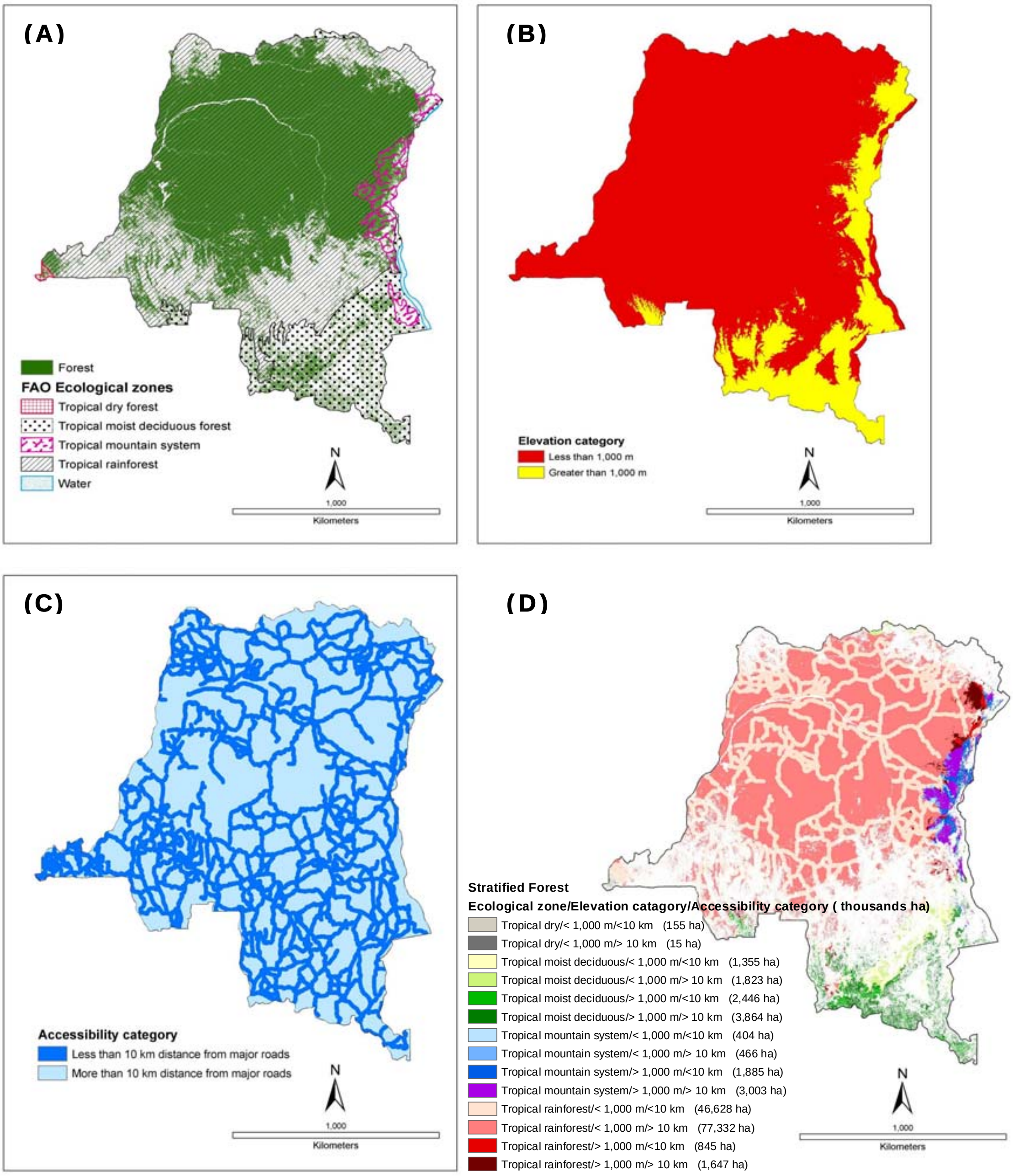
Box 4.5: Forest stratification in countries with limited data availability

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).



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 and degradation. 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 neighboring 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 emissions can be calculated.

This approach is likely the least expensive option as long as neighboring 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 case and the highest carbon stock estimate in the monitoring phase.

4.4 Estimation of Carbon Stocks of Forests Undergoing Change

4.4.1 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 time zero 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. 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 deforestation or degradation estimates are under-estimated. Likewise if CO2 emitted from the soil is excluded as a source of emissions; and as long as this exclusion is constant between the reference case and later estimations, then no exaggeration of emissions reductions occurs.

4.4.1.1 Key categories

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 (cf. Ch. 3.3).

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 4.4 a & b[19]). 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.

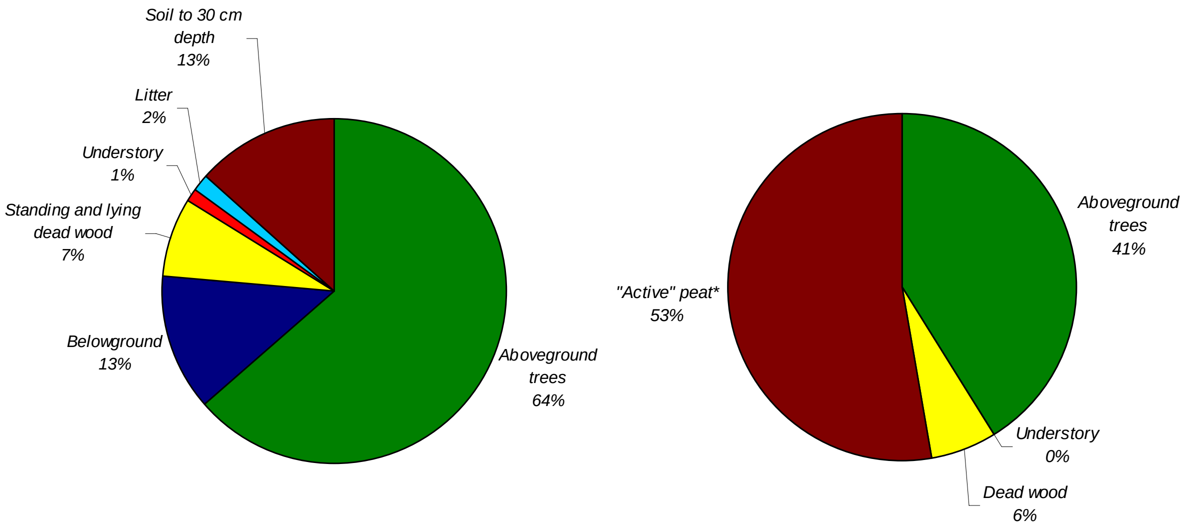


Figure 4.4: LEFT- Proportion of total stock (202 t C/ha) in each carbon pool in Noel Kempff Climate Action project (a pilot carbon project), Bolivia, and RIGHT- Proportion of total stock (236 t C/ha) in each carbon pool in peat forest in Central Kalimantan, Indonesia (active peat includes soil organic carbon, live and dead roots, and decomposing materials).

Pools can be divided by ecosystem and land use change type into key categories or minor categories. Key categories represent pools that could account for more than 25% of the total emissions resulting from the deforestation or degradation (Table 4.2).

Table 4.2: Broad guidance on key categories of carbon pools for determining assessment emphasis. Key category defined as pools potentially responsible for more than 25% 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)		

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

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 category and available financial resources.

Soils will represent a key category in peat swamp forests and mangrove forests (cf Figure 4-4b) and carbon emissions are high when deforested (see Box 4-12). 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.

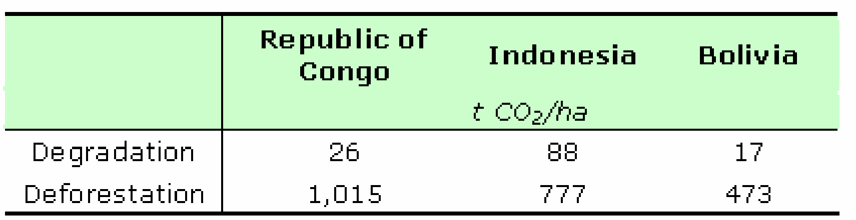
Dead wood is a key category in old growth forest where it can represent more than 10% of total biomass, in young successional forests, for example, it will not be a key category.

For carbon pools representing a fraction of the total (<25 %) it may be possible to include them at low cost if good default data are available.

Box 4.6 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.

Box 4.6: Potential emissions from deforestation and degradation in three example countries

The following table shows the decreases in the carbon stock of living trees estimated for both deforestation, and degradation through legal selective logging for three countries: Republic of Congo, Indonesia, and Bolivia. The large differences among the countries for degradation reflects the differences in intensity of timber extraction (about 3 to 22 m3/ha).



	Republic of Congo	Indonesia	Bolivia
		t CO_2/ha	
Degradation	26	88	17
Deforestation	1,015	777	473

4.4.1.2 Defining 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 4.3 (modified from Table 4.4 in IPCC GL AFOLU to exclude non-forest or non-tropical values and to account for incorrect values) then it makes sense to include roots.

Table 4.3: 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	<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 based on communications with Karel Mulroney, 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 categories 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 pools are decided on initially the same pools must 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 emissions 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—soil is collected and then must be analyzed 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 density

If the pool is a significant source of emissions as a result of deforestation or degradation it will be worth including it in the assessment if it is possible. An alternative to measurement for minor carbon pools (<25% of the total potential emission) is to include estimates from tables of default data with high integrity (peer-reviewed).

4.4.2 General approaches to estimation of carbon stocks

4.4.2.1 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 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 deforestation pressure.

<u>SubStep 1</u> – For reference emission case (and future monitoring for approach B): establish sampling plans in areas representative of the areas with recorded deforestation and/or degradation.

<u>SubStep 2</u> – For future monitoring: 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 but, for the current period, do not invest in measuring forests that are hard to access such as areas that are distant to transportation routes, towns, villages and existing farmland, and/or areas at high elevations or that experience very heavy rainfall.

4.4.2.2 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

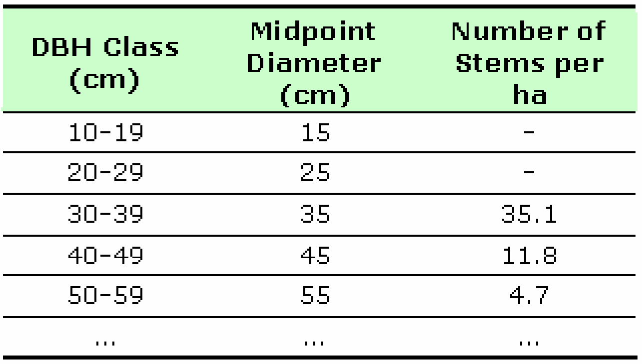
Typically forest inventories have an economic motivation. As a consequence, forest inventories worldwide are derived from good sampling design. If the inventory can be applied to a stratum, all species are included and the minimum diameter is 30 cm or less then the data will be a high enough quality with sufficiently low uncertainty for inclusion. Inventory data typically comes in two different forms:

Stand tables—these data from an 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. The mid-point diameter of the class can be used[20] 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 4-9). 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.

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. 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[21]. It is recommended that the method described here (Box 4.7) 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 4.7: 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

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[20] If information on the basal area of all the trees in each diameter class is provided, instead of using the mid point 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).

[21] Gillespie, A. J. R, S. Brown, and A. E. Lugo. 1992. Tropical forest biomass estimation from truncated stand tables. Forest Ecology and Management 48:69-88.

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 4-7).

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 can not 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 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[22]

where:

BCEF t/m^3 = biomass conversion and expansion factor (ratio of aboveground oven-dry biomass of trees [t/ha] to merchantable growing stock volume over bark [m^3/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 4.4.

Table 4.4: 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, m^3/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

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[22] 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.

- ☐ 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

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. 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 = Exp{1.300 - 0.209*Ln(VOB30)} for VOB30 < 250 m3/ha

= 1.13 for VOB30 > 250 m3/ha

See Box 4-8 for a demonstration of the use of the VEF correction factor and BCEF to estimate biomass density.

Box 4.8: 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

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 deforestation and degradation assessments.

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 will be defined in the political arena, 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.

4.4.2.3 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 period are at risk of deforestation or degradation in the future 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 4.9).

Box 4.9: Guidance on collecting new carbon stock data

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

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 readily using the methods given above. However, it would be useful in the implementation of new inventories that instead of using plot less approach for measuring trees that the actual dbh be measured and recorded. Application of allometric equations commonly acceptable in carbon studies[23] 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

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 Land Use, Land-Use Change and Forestry (available at: http://carbonfinance.org/doc/LULUCF_sourcebook_compressed.pdf)

Lacking in the sources given in Box 4.9 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 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 emissions from selective logging are described in Box 4.10.

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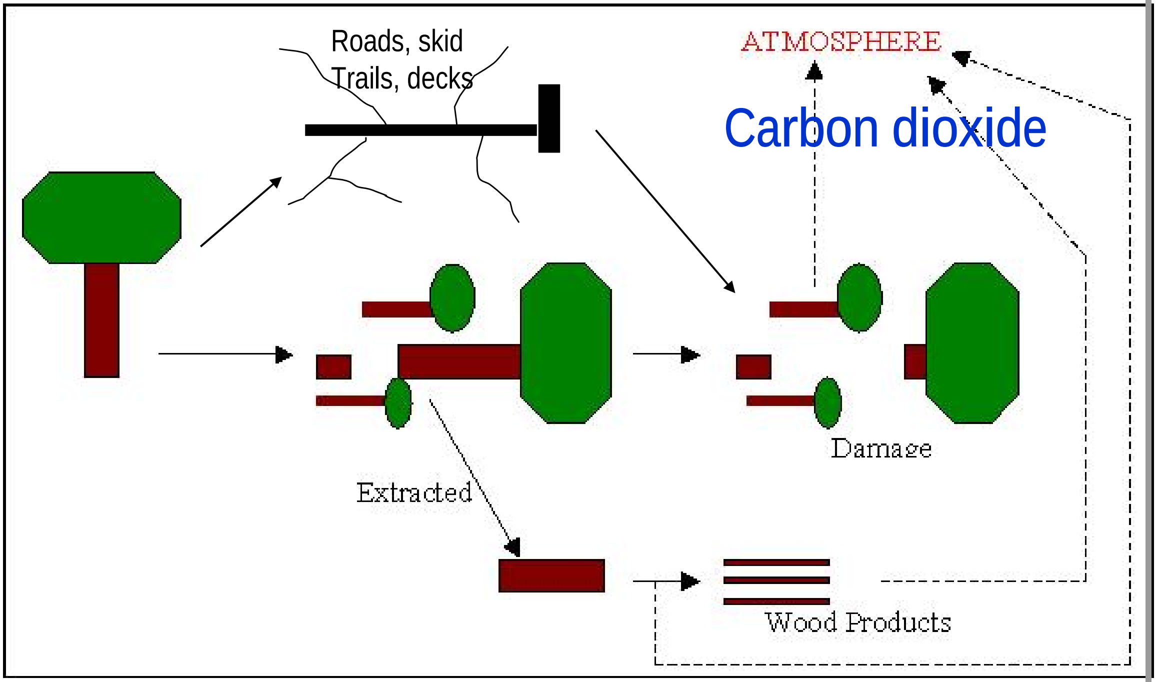
[23] E.g. Chave, J., C. Andalo, S. Brown, M. A. Cairns, J. Q. Chambers, D. Eamus, H. Folster, F. Fromard, N. Higuchi, T. Kira, J.-P. Lescure, B. W. Nelson, H. Ogawa, H. Puig, B. Riera, T. Yamakura. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145: 87-99.

Box 4.10: Estimating carbon gains and losses from logging

A model that illustrates the fate of live biomass and subsequent CO_2 emissions when a forest is selectively logged is shown below.



The total annual carbon emissions 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 logging decks) adjusted for decomposition, and (iv) the biomass that went into long term storage as wood products[24].

In equation form, the carbon impact of logging per unit area per year can be summed up as follows:

$$\boxed{\text{C Impact} = \Delta C_{livebiomass} + \Delta C_{deadbiomass} + \Delta C_{woodproducts}} \qquad \text{Eq. (1)}$$

This equation is further described as follows:

(1) $\Delta C_{livebiomass} = \Delta C_{live,\log gingdamage} + \Delta C_{timberextraction} + \Delta C_{regrowthfactor}$

The change in biomass C caused by logging damage to live trees (tops, stump, surrounding trees, trees killed from putting in skid trails, roads, decks) and timber extracted reduces the carbon stock of live biomass (data which are best collected from active logging concessions). The regrowth factor or rate accounts for a gain in

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[24] Brown S, M Burnham, M Delaney, R Vaca, M Powell, A. Moreno. 2000. Issues and challenges for forest-based carbon-offset projects: a case study of the Noel Kempff Climate Action Project in Bolivia. *Mitigation and Adaptation Strategies for Climate Change* 5:99-121.

Brown, S., Pearson, T., Moore, N., Parveen, A., Ambagis, S. and Shoch D. 2005. Deliverable 6: Impact of logging on carbon stocks of forests: Republic of Congo as a case study. Report submitted to the United States Agency for International Development; Cooperative Agreement No. EEM-A-00-03-00006-00. Available from carbonservices@winrock.org carbon resulting from the regeneration of new trees to fill the gap and potential enhanced growth of residual trees. The regrowth rate 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 quantities in (1) above can be expressed on an area basis (i.e., t C/ha) or on a m^3 of extracted timber per ha.

(2) $\Delta C_{deadbiomass} = \Delta C_{dead,\log gingdamage} \times WoodDecompositionFactor$

In areas undergoing selective logging, dead wood cannot be ignored because logging increases the size of this pool. The change in the dead wood pool should be estimated to account for decomposition that occurs over time. Research has shown that dead wood decomposes relatively slowly in tropical forests and hence this pool has a long turnover time. The damaged wood is assumed to enter the dead wood pool, where it starts to decompose, and each year more dead wood is added from harvesting, but each year some is lost because of decomposition and resulting emissions of carbon. Decomposition of dead wood is modeled as a simple exponential function based on mass of dead wood and a decomposition coefficient (proportion decomposed per year that can range from about <0.05 to 0.15 per year).

(3) $\Delta C_{woodproducts} = \Delta C_{timberextraction} \times proportion_{woodproducts}$

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.

In addition to quantifying the changes in Eq. 1, two other pieces of information are needed to fully estimate the total net emissions of CO2—these are the amount of timber extracted per unit area per year and the total area logged per year. Total emissions are then estimated as the product of total change in carbon stocks (from Eq.1), the timber extraction rate and the total area logged.

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 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 4.11.

Box 4.11: 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 fuelwood 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

4.4.3 Guidance on carbon in soils

IPCC AFOLU divides soil carbon into three pools: mineral soil organic carbon, organic soil carbon, and mineral soil inorganic carbon. The focus in this section will be on only the organic carbon component of soil.

4.4.3.1 Explanation of IPCC Tiers for soil carbon estimates

For estimating emissions from organic carbon in mineral soils, the IPCC AFOLU recommends the stock change approach but for organic carbon in organic soils such as peats, an emission factor approach is used (Table 4.5). For mineral soil organic carbon, departures in carbon stocks from a reference or base condition are calculated by applying stock change factors (specific to land-use, management practices, and inputs [e.g. soil amendment, irrigation, etc.]), equal to the carbon stock in the altered condition as a proportion of the reference carbon stock. Tier 1 assumes that a change to a new equilibrium stock occurs at a constant rate over a 20 year time period. Tiers 2 and 3 may vary these assumptions, in terms of the length of time over which change takes place, and in terms of how annual rates vary within that period. Tier 1 assumes that the maximum depth beyond which change in soil carbon stocks should not occur is 30 cm; Tiers 2 and 3 may lower this threshold to a greater depth.

Tier 1 further assumes that there is no change in mineral soil carbon in forests remaining forests. Hence, estimates of the changes in mineral soil carbon could be made for deforestation but are not needed for degradation. Tiers 2 and 3 allow this assumption to change. In the case of degradation, the Tier 2 and 3 approaches are only recommended for intensive practices that involve significant soil disturbance, not typically encountered in selective logging. In contrast, selective logging of forests growing on organic carbon soils such as the peat-swamp forests of South East Asia could result in large emissions caused by practices such as draining to remove the logs from the forest (see Box 4.12 for further details on this topic).

Table 4.5: IPCC guidelines on data and/or analytical needs for the different Tiers for soil carbon changes in deforested areas.

Soil carbon pool	Tier 1	Tier 2	Tier 3
Organic carbon in mineral soil	Default reference C stocks and stock change factors from IPCC	Country-specific data on reference C stocks & stock change factors	Validated model or direct measures of stock change through monitoring networks
Organic carbon in organic soil	Default emission factor from IPCC	Country-specific data on emission factors	Validated model or direct measures of stock change

Variability in soil carbon stocks can be large; Tier 1 reference stock estimates have associated uncertainty of up to +/- 90%. Therefore it is clear that if soil is a key category, Tier 1 estimates should be avoided.

4.4.3.2 When and how to generate a good Tier 2 analysis for soil carbon

Modifying Tier 1 assumptions and replacing default reference stock and stock change estimates with country-specific values through Tier 2 methods is recommended to reduce uncertainty for significant sources. Tier 2 provides the option of using a combination of country-specific data and IPCC default values that allows a country to more efficiently allocate its limited resources in the development of emission inventories.

How can one decide if loss of soil C during deforestation is a significant source? It is recommended that, where emissions from soil carbon are likely to represent a key subcategory of overall emissions from deforestation—that is > 25-30%, the emissions accounting should move from a Tier 1 to a Tier 2 approach for estimating carbon emissions from soil. Generally speaking, where reference soil carbon stocks equal or exceed aboveground biomass carbon, carbon emissions from soil often exceed 25% of total emissions from deforestation upon conversion to cropland, and consideration should be given to applying a Tier 2 approach to estimating emissions from soil carbon. If deforestation in an area commonly converts forests to other land uses such as pasture or other perennial crops, then the loss of soil carbon and resulting emissions is unlikely to reach 25%, and thus a Tier 1 approach would suffice.

Assessments of opportunities to improve on Tier 1 assumptions with a Tier 2 approach are summarized in Table 4.6.

Table 4.6: Opportunities to improve on Tier 1 assumptions using a Tier 2 approach.

	Tier 1 assumptions	**Tier 2 options**	**Recommendation**
Depth to which change in stock is reported	30 cm	May report changes to deeper depths	Not recommended. There is seldom any benefit in sampling to deeper depths for tropical forest soils because impacts of land conversion and management on soil carbon tend to diminish with depth - most change takes place in the top 25-30 cm.
Time until new equilibrium stock is reached	20 years	May vary the length of time until new equilibrium is achieved, referencing country-specific chronosequences or long-term studies	Recommended where a chronosequence[25] or long-term study data are available. Some soils may reach equilibrium in as little as 5-10 years after conversion, particularly in the humid tropics[26].
Rate of change in stock	Linear	May use non-linear models	Not recommended – best modeled with Tier 3-type approaches. As well, a typical 5-year reporting interval effectively "linearizes" a non-linear model and would undo the benefits of a model with finer resolution of varying annual changes.
Reference stocks	IPCC defaults	Develop country-specific reference stocks consulting other available databases or consolidating country soil data from existing sources (universities, agricultural extension services, etc.).	IPCC defaults comprehensive. Not recommended unless country-specific data are available.
Stock change factors	IPCC defaults	Develop country-specific stock change factors from chronosequence or long-term study.	IPCC defaults fairly comprehensive. Not recommended unless significant areas (that can be delineated spatially) are represented by drainage as a typical conversion practice.

The IPCC default values for reference soil carbon stocks and stock change factors are comprehensive and reflect the most recent review of changes in soil carbon with conversion of native soils. Reference stocks and stock change factors represent average conditions globally, which means that, in at least half of the cases, use of a more

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[25] A chronosequence is a series on land units that represent a range of ages after some event – they are often used to substitute time with space, e.g. a series of cropfield of various ages since they were cleared from forests (making sure they are on same soil type, slope, etc.).

[26] Detwiler, R. P. 1986. Land use change and the global carbon cycle: the role of tropical soils. Biogeochemistry 31: 1-14.

accurate and precise (higher Tier) approach will not produce a higher estimate of stocks or emissions than the Tier 1 defaults with respect to the categories covered.

Where country-specific data are available from existing sources, Tier 2 reference stocks should be constructed to replace IPCC default values. Measurements or estimates of soil carbon can be acquired through consultations with local universities, agricultural departments or extension agencies, all of which often carry out soil surveying at scales suited to deriving national or regional level estimates. It should be acknowledged however that because agricultural extension work is targeted to altered (cultivated) sites, agricultural extension agencies may have comparatively little information gathered on reference soils under native vegetation. Where data on reference sites are available, it would be advantageous if the soil carbon measurements were geo-referenced. Soil carbon data generated through typical agricultural extension work is often limited to carbon concentrations (i.e. percent carbon) only, and for this information to be usable, carbon concentrations must be paired with soil bulk density (mass per unit volume), volume of fragments > 2 mm, and depth sampled to derive a mass C per unit area of land surface (see Ch. 4.3 of the IPCC GPG report for more details about soil samples).

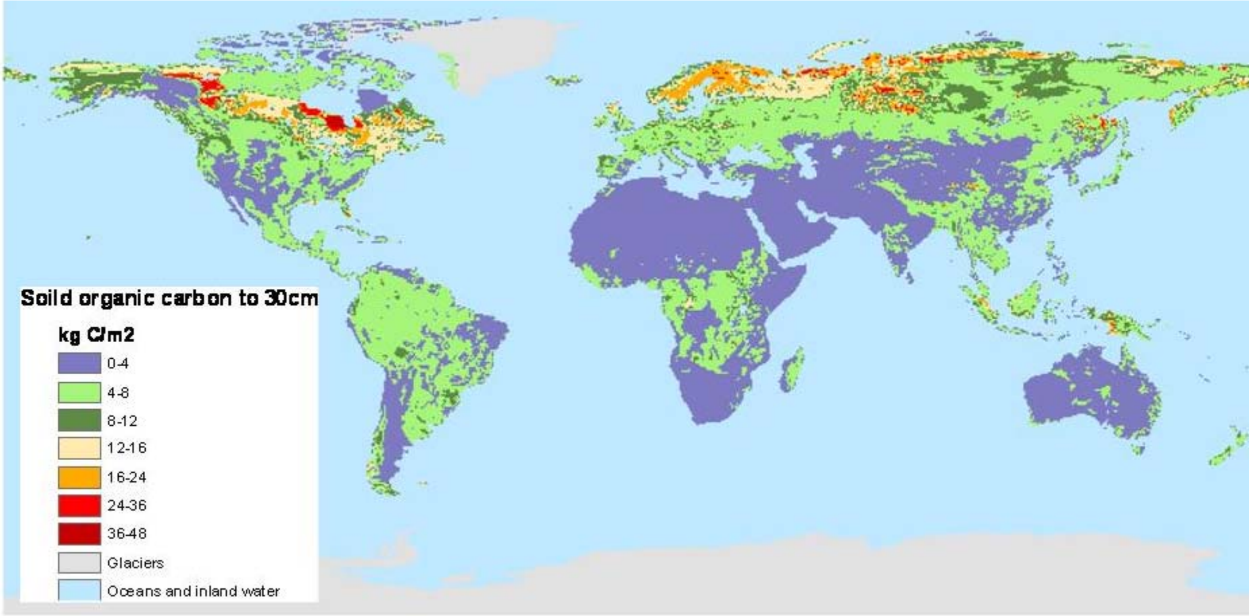
A spatially-explicit global database of soil carbon is also available from which country-specific estimates of reference stocks can be sourced. The ISRIC World Inventory of Soil Emission (WISE) Potential Database offers 5 x 5 minute grid resolution of soil organic carbon content and bulk density to 30 cm depth, and can be accessed online at:

http://www.isric.org/UK/About+Soils/Soil+data/Geographic+data/Global/WISE5by5minutes.htm

A soil carbon map is also available from the US Department of Agriculture, Natural Resources Conservation Service (Figure 4.5). This map is based on a reclassification of the FAO-UNESCO Soil Map of the World combined with a soil climate map. This map shows is little variation for soil C in the tropics with most areas showing a range in soil carbon of 40-80 t C/ha (4-8 Kg C/m^2). The soil organic carbon map shows the distribution of the soil organic carbon to 30 cm depth, and can be downloaded from:

ftp://www.daac.ornl.gov/data/global_soil/IsricWiseGrids/

Figure 4.5: Soil organic carbon map (kg/m2 or x10 t/ha; to 30 cm depth) from the global map produced by the USDA Natural Resources Conservation Service.



Existing map sources can be useful to countries for developing estimates for the reference emission period and for assisting in determining whether changes in soil carbon stocks after deforestation would be a key category or not. Deforestation could emit up to 30-40% of the carbon stock in the top 30 cm of soil during the first 5 years or so after clearing in the humid tropics. Using the soil map above and assuming the soil C content to 30 cm is 80 t C/ha, a 40% emission rate would result in 32 t C/ha being emitted in the first 5 years. If the carbon stock of the forest vegetation was 120 t C/ha (not unreasonable), then the emission of 32 t C/ha is more than 25% of the C stock in forest vegetation and could be considered a significant emissions source.

There are two factors not included in the IPCC defaults that can potentially influence carbon stock changes in soils: soil texture and soil moisture. Soil texture has an acknowledged effect on soil organic carbon stocks, with coarse sandy soils (e.g. podosols) having lower carbon stocks in general than finer texture soils such as loams or clayey soils. Thus the texture of the soil is a useful indicator to determine the likely quantity of carbon in the soil and the likely amount emitted as CO_2 upon conversion. A global data set on soil texture is available for free downloading and could be used as an indicator of the likely soil carbon content[27]. Specifically, soil carbon in coarse sandy soils, with less capacity for soil organic matter retention, is expected to oxidize more rapidly and possibly to a greater degree than in finer soils. However, because coarser soils also tend to have lower initial (reference) soil carbon stocks, conversion of these soils is unlikely to be a significant source of emissions and therefore development of a soil texture-specific stock change factor is not recommended for these soils.

Drainage of a previously inundated mineral soil increases decomposition of soil organic matter, just as it does in organic soils, and unlike the effect of soil texture, is likely to be associated with high reference soil carbon stocks. These are reflected in the IPCC default reference stocks for forests growing on wetland soils, such as floodplain forests. Drainage of forested wetland soils in combination with deforestation can thus represent a significant source of emissions. Because this factor is lacking from the IPCC default stock change factors, its effects would not be discerned using a Tier 1 approach. In other words, IPCC default stock change factors would underestimate soil carbon emissions where deforestation followed by drainage of previously inundated soils occurred. Where drainage practices on wetland soils are representative of national trends and significant areas, and for which spatial data are available, the Tier 2 approach of deriving a new, country-specific stock change factor from chronosequences or long-term studies is recommended.

Field measurements can be used to construct chronosequences that represent changes in land cover and use, management or carbon inputs, from which new stock change factors can be calculated, and many sources of methods are available (see Box 4.9). Alternatively, stock change factors can be derived from long-term studies that report measurements collected repeatedly over time at sites where land-use conversion has occurred. Ideally, multiple paired comparisons or long-term studies would be done over a geographic range comparable to that over which a resulting stock change factor will be applied, though they do not require representative sampling as in the development of average reference stock values.

Deforestation of peat swamp forests (on organic soils) represent a special case and guidance is given in Box 4.12.

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[27] Webb, R. W., C. E. Rosenzweig, and E. R. Levine. 2000. Global Soil Texture and Derived Water-Holding Capacities (Webb et al.). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/548.

Box 4.12. Emissions as a result of land use change in peat swamp forests

Peat swamp forests are found throughout Southeast Asia (Figure A). Under natural conditions, the water table depth is near the peat surface and dead organic matter accumulates under these waterlogged conditions. Many of these peat forests have been destroyed due to degradation from logging pressure, deforestation for agriculture, and burning from past land use change. In addition to the aboveground emissions that result from clearing the forest vegetation, emissions from peat continue through time because drainage causes a lowering of the water table, causing a release of CO2 into the atmosphere from peat oxidation (Figure B). If the water table is lowered by of 0.8 meters by draining, CO2 emissions are estimated at 73 tons per hectare per year. As the peat drains, it dries out and becomes more susceptible to burning. In the well-publicized 1997 fires in Indonesia, the average depth of peat burned in Central Kalimantan was 0.5 meters, resulting in a release of approximately 929 t CO2/ha (253 t C/ha)[28].

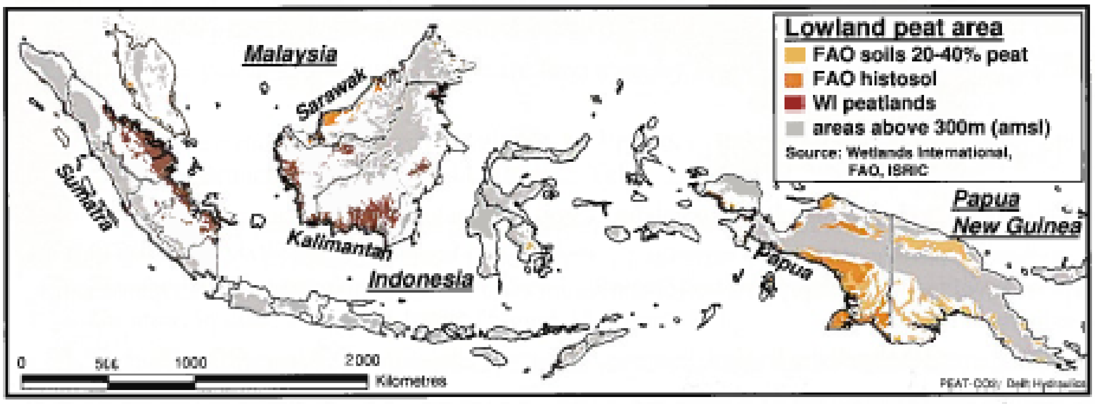

Figure A. Extent of lowland peat forests in Southeast Asia. The Wetlands International data have higher detail and accuracy than the FAO data.[29]

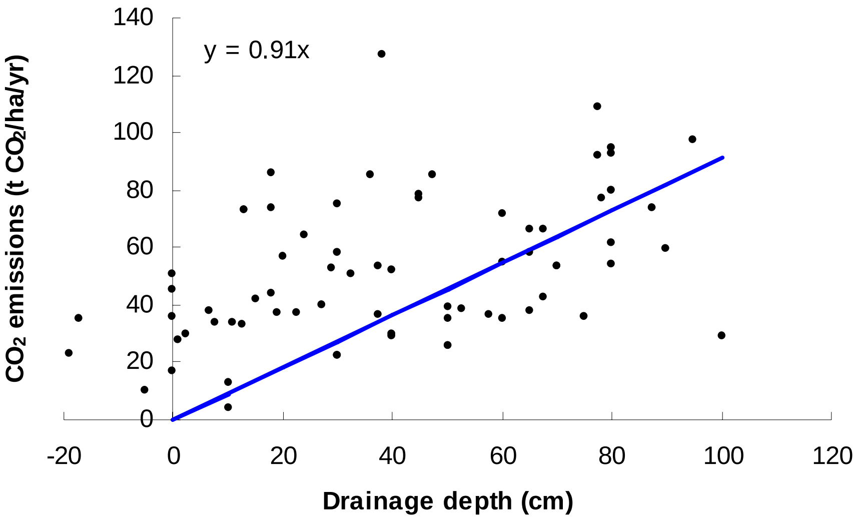

Figure B. Relation between drainage depth and CO2 emissions from decomposition (fires excluded) in tropical peat swamps[17]. Note that the average water table depth in a natural peat swamp is near the soil surface (by definition, as vegetation matter only accumulates to form peat under waterlogged conditions).

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[28] Page, S.E., Siegert, F., ORieley, J., Boehm, H.D.V., Jayak, A., & Limink, S. 2002, The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 420:61-65.

[29] Hooijer, A., Silvius, M., Wösten, H. and Page, S. (2006): PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia. Delft Hydraulics report Q3943 (2006).

4.5 Uncertainty

The uncertainty of carbon estimates should be quantified following Chapter 5 of IPCC GPG LULUCF and briefly described here. Confidence in estimates of emission reductions can only arise if the uncertainty of the estimates is included.

The uncertainty of separate components of the total carbon is defined relative to the 95 % confidence interval around the mean. The 95% confidence interval expresses the range in which the true value will lie with statistical certainty.

The Tier 1 method for combining separate uncertainties to give a total uncertainty is "Simple Propagation of Errors". Under this method the total uncertainty is equal to the square root of the sum of the squares of each of the component uncertainties.

Where the same units are being combined such as when the total uncertainty from the combined carbon pools are being assessed, then the 95 % confidence interval should be used. However, where different units are employed such as carbon biomass and forest area, uncertainty is equal to the 95% confidence interval as a percentage of the mean ((95% confidence interval/mean) x 100).

$$U_{total} = \sqrt{U_1^2 + U_2^2 + ... + U_n^2}$$

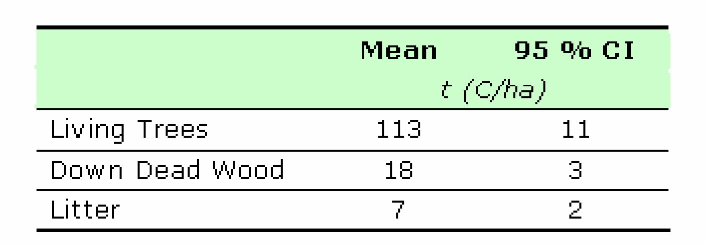
Where:

Utotal = total uncertainty

Ui = uncertainty associated with each of the component quantities

This method should be used with caution if there is a high level of correlation between components of the total error or if any of the component uncertainties is high (a standard deviation greater than 30% of the mean). Even if these tests are failed the equation can still be used to give approximate results. All assessments should include at least a simple Tier 1-type of analysis of propagation of uncertainties. An example is shown in Box 4.13.

BOX 4.13: Example of a Tier 1 uncertainty analysis



	Mean	95 % CI
	t (C/ha)	
Living Trees	113	11
Down Dead Wood	18	3
Litter	7	2

Therefore the total stock is 138 t C/ha and the uncertainty =

$$\sqrt{11^2 + 3^2 + 2^2} = 11.6tC/ha$$

The total uncertainty is 8% of the mean total C stock of 138 t C/ha

The Tier 2 method is a Monte Carlo type analysis. Monte Carlo analyzes model uncertainty through selecting random values from probability distributions for parameters and measuring the effect on total stocks. Either training in the use of software packages that automatically provide Monte Carlo type analyses or contracting an expert in Monte Carlo analysis would be needed to implement this higher level method.

5 METHODS FOR ESTIMATING CO2 EMISSIONS FROM DEFORESTATION AND FOREST DEGRADATION

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5.1 Scope of this Chapter

This chapter describes the methodologies that can be used to estimate carbon emissions from deforestation and forest degradation. It builds on Chapters 3 and 4 of this Sourcebook, which describe procedures for collecting the input data for these methodologies, namely areas of land use and land-use change (Chapter 3), and carbon stocks and changes in carbon stocks (Chapter 4).

The methodologies described here are derived from the 2006 IPCC AFOLU Guidelines and the 2003 IPCC GPG-LULUCF, and focus on the Tier 2 IPCC methods, as these require country-specific data but do not require expertise in complex models or detailed national forest inventories.

The AFOLU Guidelines and GPG-LULUCF define six categories of land use[30] that are further sub-divided into subcategories of land remaining in the same category (e.g., Forest Land Remaining Forest Land) and of land converted from one category to another (e.g., Land converted to Cropland). The land conversion subcategories are then divided further based on initial land use (e.g., Forest Land converted to Cropland, Grassland converted to Cropland). This structure was designed to be broad enough to classify all land areas in each country and to accommodate different land classification systems among countries. The structure allows countries to account for, and track over time, their entire land area, and enables greenhouse gas estimation and reporting to be consistent and comparable among countries. For REDD estimation, each subcategory could be further subdivided by climatic, ecological, soils, and/or anthropogenic disturbance factors, depending upon the level of stratification chosen for area change detection and carbon stock estimation (see Chapters 3 and 4).

For the purposes of this Sourcebook, five IPCC land-use subcategories are relevant. Although the term deforestation within the REDD mechanism remains to be defined, it is likely to be encompassed by the four land-use change subcategories defined for conversion of forests to non-forests (see Ch. 2.3[31]). Forest degradation, or the long-term loss of carbon stocks that does not qualify as deforestation is encompassed by the IPCC land-use subcategory “Forest Land Remaining Forest Land.” The methodologies that are presented here are based on the sections of the AFOLU Guidelines and the GPG-LULUCF that pertain to these land-use subcategories.

Within each land-use subcategory, the IPCC methods track changes in carbon stocks in five pools (see Chapter 4). The IPCC emission/removal estimation methodologies cover all of these carbon pools. Total net carbon emissions equal the sum of emissions and removals for each pool. However, as is discussed in Chapter 4, REDD accounting schemes may or may not include all carbon pools. Which pools to include will depend on decisions by policy makers the could be driven by such factors as financial resources,

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[30] The names of these categories are a mixture of land-cover and land-use classes, but are collectively referred to as ‘land-use’ categories by the IPCC for convenience.

[31] The subcategory “Land Converted to Wetlands” includes the conversion of forest land to flooded land, but as this land-use change is unlikely to be important in the context of REDD accounting, and measurements of emissions from flooded forest lands are relatively scarce and highly variable, this land-use change is not addressed further in this chapter.

availability of existing data, ease and cost of measurement, and the principle of conservativeness.

5.2 Linkage to 2006 IPCC Guidelines

Table 5-1 lists the sections of the AFOLU Guidelines that describe carbon estimation methods for each land-use subcategory. This table is provided to facilitate searching for further information on these methods in the AFOLU Guidelines, which can be difficult given the complex structure of this volume. To review greenhouse gas estimation methods for a particular land-use category in the AFOLU Guidelines, one must refer to two separate chapters: a generic methods chapter (Chapter 2) and the land-use category chapter specific to that land-use category (i.e., either Chapter 4, 5, 6, 7, 8, or 9). The methods for a particular land-use subcategory are contained in sections in each of these chapters.

Table 5.1: Locations of Carbon Estimation Methodologies in the 2006 AFOLU Guidelines

Land-Use Category (Relevant Land-Use Category Chapter in AFOLU Guidelines)	**Land-Use Subcategory (Subcategory Acronym)**	**Sections in Relevant Land-Use Category Chapter (Chapter 4, 5, 6, 8, or 9)**	**Sections in Generic Methods Chapter (Chapter 2)**
Forest Land (Chapter 4)	Forest Land Remaining Forest Land (FF)	4.2.1 4.2.2 4.2.3	2.3.1.1 2.3.2.1 2.3.3.1.
Cropland (Chapter 5)	Land Converted to Cropland (LC)	5.3.1 5.3.2 5.3.3	2.3.1.2 2.3.2.2 2.3.3.1
Grassland (Chapter 6)	Land Converted to Grassland (LG)	6.3.1 6.3.2 6.3.3	2.3.1.2 2.3.2.2 2.3.3.1
Settlements (Chapter 8)	Land Converted to Settlements (LS)	8.3.1 8.3.2 8.3.3	2.3.1.2 2.3.2.2 2.3.3.1
Other Land (Chapter 9)	Land Converted to Other Land (LO)	9.3.1 9.3.2 9.3.3	2.3.1.2 2.3.2.2 2.3.3.1

Information and guidance on uncertainties relevant to estimation of emissions from land use and land-use change are located in various chapters of two separate volumes of the 2006 IPCC Guidelines. Chapter 3 of the General Guidance and Reporting volume (Volume 1) of the 2006 IPCC Guidelines provides detailed, but non-sector-specific, guidance on sources of uncertainty and uncertainty estimation methodologies. Land-use subcategory-specific information about uncertainties for specific carbon pools and land uses is provided in each of the land-use category chapters (i.e., Chapter 4, 5, 6, 7, 8, or 9) of the AFOLU Guidelines (Volume 4).

5.3 Organization of this Chapter

The remainder of this chapter discusses carbon emission estimation for deforestation and forest degradation:

- Section 5.4 addresses basic issues related to carbon estimation, including the concept of carbon transfers among pools, emission units, and fundamental methodologies for estimating annual changes in carbon stocks.

- ☐ Section 5.5 describes methods for estimating carbon emissions from deforestation based on the generic IPCC methods for land converted to a new land-use category, and on the IPCC methods specific to types of land-use conversions from forests.
- ☐ Section 5.6 describes methods for estimating carbon emissions from forest degradation based on the IPCC methods for "Forest Land Remaining Forest Land."
- ☐ Section 5.7 describes methods for dealing with uncertainties.

5.4 Fundamental Carbon Estimating Issues

The overall carbon estimating method used here is one in which net changes in carbon stocks in the five terrestrial carbon pools are tracked over time. For each strata or sub-division of land area within a land-use category, the sum of carbon stock changes in all the pools equals the total carbon stock change for that stratum. In the REDD context, discussions center on gross emissions thus estimating the decrease in total carbon stocks, which is equated with emissions of CO_2 to the atmosphere, is all that is needed at this time. For deforestation at a Tier 1 level, this simply translates into the carbon stock of the forest being deforested because it is assumed that this goes to zero when deforested. However, a decrease in stocks in an individual pool may or may not represent an emission to the atmosphere because an individual pool can change due to both carbon transfers to and from the atmosphere, and carbon transfers to another pool (e.g., the transfer of biomass to dead wood during logging). Disturbance matrices are discussed below as a means to track carbon transfers among pools at higher Tier levels and thereby avoid over- or underestimates of emissions and improve uncertainty estimation.

In the methods described here, all estimates of changes in carbon stocks (e.g., biomass growth, carbon transfers among pools) are in mass units of carbon (C) per year, e.g., t C/yr. To be consistent with the AFOLU Guidelines, equations are written so that net carbon emissions (stock decreases) are negative.[32]

There are two fundamentally different, but equally valid, approaches to estimating carbon stock changes: 1) the stock-based or stock-difference approach and 2) the process-based or gain-loss approach. These approaches can be used to estimate stock changes in any carbon pool, although as is explained below, their applicability to soil carbon stocks is limited. The stock-based approach estimates the difference in carbon stocks in a particular pool at two points in time (Equation 5-1). This method can be used when carbon stocks in relevant pools have been measured and estimated over time, such as in national forest inventories. The process-based or gain-loss approach estimates the net balance of additions to and removals from a carbon pool (Equation 5-2). In the REDD context, gains only result from carbon transfer from another pool (e.g., transfer from a biomass pool to a dead organic matter pool due to disturbance), and losses result from carbon transfer to another pool and emissions due to harvesting, decomposition or burning. This type of method is used when annual data such as biomass growth rates and wood harvests are available. In reality, a mix of the stock-difference and gain-loss approaches can be used as discussed further in this chapter.

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[32] To be consistent with the national greenhouse gas inventory reporting tables established by the IPCC, in which emissions are reported as positive values, emissions would need to be multiplied by negative one (-1).

Equation 5.1

Annual Carbon Stock Change in a Given Pool as an Annual Average Difference in Stocks (Stock-Difference Method)

$$\Delta C = \frac{(C_{t2} - C_{t1})}{(t_2 - t_1)}$$

Where:

ΔC = annual carbon stock change in pool (t C/yr)

C_{t1} = carbon stock in pool in at time t_1 (t C)

C_{t2} = carbon stock in pool in at time t_2 (t C)

Note: the carbon stock values for some pools may be in t C/ ha, in which case the difference in carbon stocks will need to be multiplied by an area.

Equation 5.2

Annual Carbon Stock Change in a Given Pool As a Function of Annual Gains and Losses (Gain-Loss Method)

$$\Delta C = \Delta C_G - \Delta C_L$$

Where:

ΔC = annual carbon stock change in pool (t C/yr)

ΔC_G = annual gain in carbon (t C/yr)

ΔC_L = annual loss of carbon (t C/yr)

The stock-difference method is suitable for estimating emissions caused by both deforestation and forest degradation, and can apply to all carbon pools.[33] The carbon stock for any pool at time t_1 will represent the carbon stock of that pool in the forest of a particular stratum (see Chapter 4), and the carbon stock of that pool at time t_2 will either be zero (the Tier 1 default value for biomass and dead organic matter immediately after deforestation) or the value for the pool under the new land use (see section 5.5.2) or the value for the pool under the resultant degraded forest. If the carbon stock values are in units of t C/ha, the change in carbon stocks, ΔC, is then multiplied by the area deforested or degraded for that particular stratum, and then divided by the time interval to give an annual estimate.

Estimating the change in carbon stock using the gain-loss method (Equation 5-2) is not likely to be useful for deforestation estimating with a Tier 1 or Tier 2 method, but could be used for Tier 3 approach for biomass and dead organic matter involving detailed forest inventories and/or simulation models. However, the gain-loss method can be used for forest degradation to account for the biomass and dead organic matter pools with a Tier 2 or Tier 3 approach. Biomass gains would be accounted for with rates of growth, and biomass losses would be accounted for with data on timber harvests, fuelwood removals, and transfers to the dead organic matter pool due to disturbance. Dead

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[33] Although in theory the stock-difference approach could be used to estimate stock changes in both mineral soils and organic soils, this approach is unlikely to be used in practice due to the expense of measuring soil carbon stocks. The IPCC has adopted different methodologies for soil carbon, which are described below.

organic matter gains would be accounted for with transfers from the live biomass pools and losses would be accounted for with rates of dead biomass decomposition.

5.5 Estimation of Emissions from Deforestation

5.5.1 Disturbance Matrix Documentation

Land-use conversion, particularly from forests to non-forests, can involve significant transfers of carbon among pools. The immediate impacts of land conversion on the carbon stocks for each forest stratum can be summarized in a matrix, which describes the retention, transfers, and releases of carbon in and from the pools in the original land-use due to conversion (Table 5-2). The level of detail on these transfers will depend on the decision of which carbon pools to include, which in turn will depend on the key category analysis (see Table 4.2 in Chapter 4). The disturbance matrix defines for each pool the proportion of carbon that remains in the pool and the proportions that are transferred to other pools. Use of such a matrix in carbon estimating will ensure consistency of estimating among carbon pools, as well as help to achieve higher accuracy in carbon emissions estimation. Even if all the data in the matrix are not used, the matrix can assist in estimation of uncertainties.

Table 5.2 Example of a disturbance matrix for the impacts of deforestation on carbon pools (Table 5.7 in the AFOLU Guidelines). Impossible transfers are blacked out. In each blank cell, the proportion of each pool on the left side of the matrix that is transferred to the pool at the top of each column is entered. Values in each row must sum to 1.

To From	Above-ground biomass	Below-ground biomass	Dead wood	Litter	Soil organic matter	Harvested wood products	Atmo-sphere	Sum of row (must equal 1)
Aboveground biomass		▨						
Belowground biomass	▨	▨	▨	▨		▨		
Dead wood	▨	▨				▨		
Litter	▨	▨	▨			▨		
Soil organic matter	▨	▨	▨	▨		▨		

5.5.2 Changes in Carbon Stocks of Biomass

The IPCC methods for estimating the annual carbon stock change on land converted to a new land-use category include two components:

- One accounts for the initial change in carbon stocks due to the land conversion, e.g., the change in biomass stocks due to forest clearing and conversion to say cropland.
- The other component accounts, in the REDD context, only for the gradual carbon loss during a transition period to a new steady-state system.

For the biomass pools, conversion to annual cropland and settlements generally contain lower biomass and steady-state is usually reached in a shorter period (e.g., the default assumption for annual cropland is 1 year). The time period needed to reach steady state in perennial cropland (e.g., orchards) or even grasslands, however, is typically more than one year. The inclusion of this second component will likely become more important for future monitoring of the performance of REDD as countries consider moving into a Tier 3 approach and implement an annual or bi-annual monitoring system.

The initial change in biomass (live or dead) stocks due to land-use conversion is estimated using a stock-difference approach in which the difference in stocks before and after conversion is calculated for each stratum of land converted. Equation 5-3 (below) is the equation presented in the AFOLU Guidelines for biomass.

Equation 5.3

Initial Change in Biomass Carbon Stocks on Land Converted to New Land-Use Category

(Stock-Difference Type Method)

$$\Delta C_{CONV} = \sum \left[\left(B_{AFTERi} - B_{BEFOREi} \right) \cdot \Delta A_i \right] \cdot CF$$

Where:

ΔC_{CONV} =initial change in biomass carbon stocks on land converted to another land-use category (t C yr^{-1})

B_{AFTERi} =biomass stocks on land type *i* immediately after conversion (t dry matter/ha)

$B_{BEFOREi}$ =biomass stocks on land type *i* before conversion (t dry matter/ha)

ΔA_i = area of land type *i* converted (ha)

CF = carbon fraction (t C /t dm)

i = stratum of land

The Tier 1 default assumption for biomass and dead organic matter stocks immediately after conversion of forests to non-forests is that they are zero, whereas the Tier 2 method allows for the biomass and dead organic matter stocks after conversion to have non-zero values. Disturbance matrices (e.g., Table 5.2) can be used to summarize the fate of biomass and dead organic matter stocks, and to ensure consistency among pools.

The biomass stocks immediately after conversion will depend on the amount of live biomass removed during conversion. During conversion, aboveground biomass may be removed as timber of fuelwood, burned and the carbon emitted to the atmosphere or transferred to the dead wood pool, and/or cut and left on the ground as deadwood; and belowground biomass may be transferred to the soil organic matter pool (See Ch 4.1.1.3). Estimates of default values for the biomass stocks on croplands and grasslands are given in the AFOLU Guidelines in Table 5.9 (croplands) and Table 6.4 (grasslands). The dead organic matter (DOM) stocks immediately after conversion will depend on the amount of live biomass killed and transferred to the DOM pools, and the amount of DOM carbon released to the atmosphere due to burning and decomposition. In general, croplands (except agroforestry systems) and settlements will have little or no dead wood and litter so the Tier 1 ‘after conversion’ assumption for these pools may be reasonable for these land uses.

A two-component approach for biomass and DOM may not be necessary in REDD estimating. If land-use conversions are permanent, and all that one is interested in is the total change in carbon stocks, then all that is needed is the carbon stock prior to conversion, and the carbon stocks after conversion once steady state is reached. These data would be used in a stock difference method (Equation 5.1), with the time interval the period between land-use conversion and steady-state under the new land use.

5.5.3 Changes in Soil Carbon Stocks

The IPCC Tier 2 method for mineral soil organic carbon is basically a combination of a stock-difference method and a gain-loss method (Equation 5-4). (The first part of Equation 5-4 [for $\Delta C_{Mineral}$] is essentially a stock-difference equation, while the second part [for SOC] is essentially a gain-loss method with the gains and losses derived from the product of reference carbon stocks and stock change factors). The reference carbon stock is the soil carbon stock that would have been present under native vegetation on that stratum of land, given its climate and soil type.

Equation 5.4

Annual Change in Organic Carbon Stocks in Mineral Soils

$$\Delta C_{Mineral} = \frac{\left(SOC_0 - SOC_{(0-T)}\right)}{D}$$

$$SOC = \sum_{C,S,i} \left(SOC_{REF_{C,S,i}} \cdot F_{LU_{C,S,i}} \cdot F_{MG_{C,S,i}} \cdot F_{I_{C,S,i}} \cdot \Delta A_{C,S,i}\right)$$

Where:

$\Delta C_{Mineral}$ = annual change in organic carbon stocks in mineral soils (t C yr^{-1})

SOC_0 = soil organic carbon stock in the last year of the inventory time period (t C)

$SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period (t C)

T = number of years over a single inventory time period (yr)

D = Time dependence of stock change factors which is the default time period for transition between equilibrium SOC values (yr). 20 years is commonly used, but depends on assumptions made in computing the factors F_{LU}, F_{MG}, and F_I. If T exceeds D, use the value for T to obtain an annual rate of change over the inventory time period (0-T years).

c represents the climate zones, *s* the soil types, and *i* the set of management systems that are present in a country

SOC_{REF} = the reference carbon stock (t C ha^{-1})

F_{LU} = stock change factor for land-use systems or sub-system for a particular land use (dimensionless)

F_{MG} = stock change factor for management regime (dimensionless)

F_I = stock change factor for input of organic matter (dimensionless)

A = land area of the stratum being estimated (ha)

The land areas in each stratum being estimated should have common biophysical conditions (i.e., climate and soil type) and management history over the inventory time period. Also disturbed forest soils can take many years to reach a new steady state (the IPCC default for conversion to cropland is 20 years).

Countries may not have sufficient country-specific data to fully implement a Tier 2 approach for mineral soils, in which case a mix of country-specific and default data may be used. Default data for reference soil organic carbon stocks can be found in Table 2.3 of the AFOLU Guidelines (see also Ch 4.4.3). Default stock change factors can be found in the land-use category chapters of the AFOLU Guidelines (Chapter 4, 5, 6, 7, 8, and 9).

The IPCC Tier 2 method for organic soil carbon is an emission factor method that employs annual emission factor that vary by climate type and possibly by management system (Equation 5.5). However, empirical data from many studies on peat swamp soils in Indonesia could be used in such cases—see Box 4.12 (Ch. 4).

Equation 5.5

Annual Carbon Loss from Drained Organic Soils

$$L_{Organic} = \sum_{C} (A \cdot EF)_C$$

Where:

$L_{Organic}$ = annual carbon loss from drained organic soils (t C yr^{-1})

A_c = land area of drained organic soils in climate type c (ha)

EF_c = emission factor for climate type c (t C yr^{-1})

Note that land areas and emission factors can also be disaggregated by management system, if there are emissions data to support this.

This methodology can be disaggregated further into emissions by management systems in addition to climate type if appropriate emission factors are available. Default (Tier 1) emission factors for drained forest, cropland, and grassland soils are found in Tables 4.6, 5.6, and 6.3 of the AFOLU Guidelines.

5.6 Estimation of Emissions from Forest Degradation

5.6.1 Changes in Carbon Stocks

For degradation, the main changes in carbon stocks occur in the vegetation (see Table 4.2 in Ch 4). As is discussed in Ch 4, estimation of soil carbon emissions is only recommended for intensive practices that involve significant soil disturbance. Selective logging for timber or fuelwood, whether legal or illegal, in forests on mineral soil does not typically disturb soils significantly. However, selective logging of forests growing on organic soils, particularly peatswamps, could result in large emissions caused by practices such as draining to remove the logs from the forest, and then often followed by fires (see Box 4.12 in Ch 4). However, in this section guidance is provided only for the emissions from biomass.

The AFOLU Guidelines recommend either a stock-difference method (Equation 5-1) or a gain-loss method (Equation 5-2) for estimating the annual carbon stock change in "Forests Remaining Forests". In general, both methods are applicable for all tiers. With a gain-loss approach for estimating emissions, biomass gains would be accounted for with rates of growth in trees after logging, and biomass losses would be accounted for with data on timber harvests, fuelwood removals, and transfers of live to the dead organic matter pool due to disturbance (also see Box 4.10 in Ch. 4 for more guidance on improvements for this approach). With a stock-difference approach, carbon stocks in each pool would be estimated both before and after degradation (e.g. a timber harvest), and the difference in carbon stocks in each pool calculated.

The decision regarding whether a stock-difference method or a gain-loss method is used will depend largely on the availability of existing data and resources to collect additional data. Estimating the carbon impacts of logging may lend itself more readily to the gain-loss approach, while estimating the carbon impacts of fire may lend itself more readily to the stock-difference approach. For example, in the AFOLU Guidelines, details are given for using the gain-loss method for logging. This approach could be used for all forms of biomass extraction (timber and fuelwood, legally and illegally extracted) and experience has shown that if applied correctly can produce more accurate and precise emission estimates cost effectively (see Box 4.10 in Ch. 4).

For Forests Remaining Forests, the Tier 1 assumption is that net carbon stock changes in DOM are zero, whereas in reality dead wood can decompose relatively slowly, even in tropical humid climates. Both logging and fires can significantly influence stocks in the dead wood and litter pools, so countries that are experiencing significant changes in their forests due to degradation are encouraged to develop domestic data to estimate the impact of these changes on dead organic matter. It is recommended that the impacts of degradation on each carbon pool for each forest stratum be summarized in a matrix as shown in Table 5.2 above.

5.7 Estimation of uncertainties

Estimates of carbon emissions from deforestation and forest degradation need to include quantitative estimates of uncertainties. Chapters 3 and 4 describe sources of uncertainty, and approaches for estimating uncertainties, in the activity data and emission factors used in REDD accounting. This section presents the IPCC approaches for estimating the combined uncertainties of activity data and emission factors. This will improve confidence in emission estimates.

Using the simplest method, "Propagation of Errors" approach (see Ch. 4.5), the total uncertainty is calculated as shown in Equation 5-6. When different units are employed such as carbon biomass and forest area change, uncertainty is equal to the 95% confidence interval as a percentage of the mean ([95% confidence interval/mean] x 100).

Equation 5.6

Combined Uncertainties – Propagation of Error Approach

$$U_{total} = \sqrt{U_1^2 + U_2^2 + ... + U_n^2}$$

Where:

U_{total} = total uncertainty

U_i = uncertainty associated with each of the component quantities

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A demonstration of the application of this equation to a simple example is given in Box 5.1.

BOX 5.1: Example of a Tier 1 analysis that combines uncertainty in area change and on the carbon stock

	Mean	**95% C.I.**	**Uncertainty *% of mean***
Area change (ha)	10,827	823	8
Carbon stock (t C/ha)	148	22.2	15

Therefore the total carbon stock loss over the stratum is:

10,827 * 148 = 1,602,396 t C

And the uncertainty =

$$\sqrt{8^2 + 15^2} = 17\%$$

17% of 1,602,396 = 272,407 t C

The second IPCC approach for estimating combined uncertainties is a Monte Carlo type analysis (see Ch. 4.5 for more details). However, for most cases where only the area change and carbon stock of forests being changed enters into the equation—as in equation 5.3, this simple approach will suffice.

6 GUIDANCE ON REPORTING

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6.1 Issues and challenges in reporting

6.1.1 The importance of good reporting

Under the UNFCCC, information reported in greenhouse gas (GHG) inventories represents an essential link between science and policy, providing the means by which the COP can monitor progress made by Parties in meeting their commitments and in achieving the Convention's ultimate objectives. In any international system in which an accounting procedure is foreseen - as in the Kyoto Protocol and likely also in a future REDD mechanism – the information reported in a Party's GHG inventory represents the basis for assessing each Party's performance as compared to its commitments or reference scenario, and therefore represents the basis for assigning eventual incentives or penalties.

The quality of GHG inventories relies not only upon the robustness of the science underpinning the methodologies and the associated credibility of the estimates – but also on the way this information is compiled and presented. Information must be well documented, transparent and consistent with the reporting requirements outlined in the UNFCCC guidelines.

6.1.2 Overview of the Chapter

Section 6.2 gives an overview of the current reporting requirements under UNFCCC, including the general underlying principles. The typical structure of a GHG inventory is illustrated, including an example table for reporting C stock changes from deforestation.

Section 6.3 outlines the major challenges that developing countries will likely encounter when implementing the reporting principles described in section 6.2.

Section 6.4 elaborates concepts already agreed upon in a UNFCCC context and describes how a conservative approach may help to overcome some of the difficulties described in Section 6.3.

6.2 Overview of reporting principles and procedures

6.2.1 Current reporting requirements under the UNFCCC

Under the UNFCCC, all Parties are required to provide national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol. To promote the provision of credible and consistent GHG information, the COP has developed specific reporting guidelines that detail standardized requirements. Although these requirements differ across Parties, they are similar in that they are based on IPCC methodologies and aim to produce a full, accurate, transparent, consistent and comparable reporting of GHG emissions and removals.

At present, detailed reporting guidelines exist for the annual GHG inventories of Annex I Parties (UNFCCC 2004)[34], while only generic guidance is available for the preparation of national communications from non-Annex I Parties[35]. This difference reflects the fact that Annex I (AI) Parties are required to report detailed data on an annual basis that are subject to in-depth review by teams of independent experts, while Non-Annex I Parties (NAI) currently report less often and in less detail. As a result, their national communications are not subject to in-depth reviews.

However, given the potential relevance of a future REDD mechanism - and the consequent need for robust and defensible estimates - the reporting requirements of NAI Parties on emissions from deforestation will certainly become more stringent and may come close to the level of detail currently required from AI Parties. This tendency is confirmed by recent documents agreed during REDD negotiations – i.e. the demonstration REDD activities should produce estimates that are "*results based, demonstrable, transparent, and verifiable, and estimated consistently over time*"[36]. Therefore, although at present it is not possible to foresee the exact reporting requirements of a future REDD mechanism, they will likely follow the general principles and procedures currently valid for AI parties and outlined in the following section.

6.2.2 Inventory and reporting principles

Under the UNFCCC, there are five general principles which should guide the estimation and the reporting of emissions and removals of GHGs: Transparency, Consistency Comparability Completeness and Accuracy. Although some of these principles have been already discussed in previous chapters, below are summarized and their relevance for the reporting is highlighted:

- *Transparency*, i.e. all the assumptions and the methodologies used in the inventory should be clearly explained and appropriately documented, so that anybody could verify its correctness.

- *Consistency*, i.e. the same definitions and methodologies should be used along time. This should ensure that differences between years and categories reflect real differences in emissions. Under certain circumstances, estimates using different methodologies for different years can be considered consistent if they have been calculated in a transparent manner. Recalculations of previously submitted estimates are possible to improve accuracy and/or completeness, providing that all the relevant information is properly documented. In a REDD context, consistency also means that all the lands and all the carbon pools which have been reported in the reference period must to be tracked in the future (in the Kyoto language it is said "once in, always in"). Similarly, the inclusion of new sources or sinks which have existed since the reference period but were not previously reported (e.g., a carbon pool), should be reported for the reference period and all subsequent years for which a reporting is required.

- *Comparability* across countries. For this purpose, Parties should follow the methodologies and standard formats (including the allocation of different source/sink category) provided by the IPCC and agreed within the UNFCCC for estimating and reporting inventories (see also chapter 2.1). It shall be noted that the comparability principle may be extended also to definitions (e.g. definition of forest) and estimates (e.g. forest area, average C stock) provided by the same Party to different international

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[34] UNFCCC 2004 Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual inventories (FCCC/SBSTA/2004/8).

[35] UNFCCC 2002 Guidelines for the preparation of national communications from Parties not included in Annex I to the Convention (FCCC/CP/2002/7/Add.2).

[36] Decision -/CP.13. http://unfccc.int/files/meetings/cop_13/application/pdf/cp_redd.pdf.

organizations (e.g. UNFCCC, FAO). In that case, any discrepancy should be adequately justified.

- *Completeness*, meaning that estimates should include – for all the relevant geographical coverage – all the agreed categories, gases and pools. When gaps exist, all the relevant information and justification on these gaps should be documented in a transparent manner.

- *Accuracy*, in the sense that estimates should be systematically neither over nor under the true value, so far as can be judged, and that uncertainties are reduced so far as is practicable. Appropriate methodologies should be used, in accordance with the IPCC, to promote accuracy in inventories and to quantify the uncertainties in order to improve future inventories.

Furthermore, these principles also guide the process of independent review of all the GHG inventories submitted by AI Parties to the UNFCCC.

6.2.3 Structure of a GHG inventory

A national inventory of GHG anthropogenic emissions and removals is typically divided into two parts:

Reporting Tables are a series of standardized data tables that contain mainly quantitative (numerical) information. Box 6.1 shows an example table for reporting C stock changes following deforestation (modified from Kyoto Protocol LULUCF tables for illustrative purposes only). Typically, these tables include columns for:

- *The initial and final land-use category*. Additional stratification is encouraged (in a separate column for subcategories) according to criteria such as climate zone, management system, soil type, vegetation type, tree species, ecological zones, national land classification or other factors.

- The "*activity data*", i.e., area of land (in thousands of ha) subject to gross deforestation and degradation (see Ch. 3)

- *The* "*emission factors*", i.e., the C stock changes per unit area deforested or degraded, separated for each carbon pool (see Ch. 4). The term "implied factors" means that the reported values represent an average within the reported category or subcategory, and serves mainly for comparative purposes.

- *The total change in C stock*, obtained by multiplying each activity data by the relevant emission C stock change factor.

- *the total emissions* (expressed as CO_2).

Box 6-1: Example of a typical reporting table for reporting C stock changes following deforestation.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES		ACTIVITY DATA	IMPLIED CARBON STOCK CHANGE FACTORS (2)						Implied emission factor per area (3)	CHANGE IN CARBON STOCK (2)						Total CO_2 emissions (3)
			carbon stock change per **unit area** in:							carbon stock change in:						
			biomass		dead organic matter		soils			Biomass		dead organic matter		soils		
Land-Use Category	Sub-division (1)	Total area (kha)	above-ground	below-ground	dead wood	litter	mineral	organic		above-ground	below-ground	dead wood	litter	mineral	organic	
			(Mg C/ha)						(Mg CO_2/ha)	(Gg C)						(Gg CO_2)
A. Total Deforestation																
1. Forest Land converted to Cropland	(specify)															
	(specify)															
2. Forest Land converted to Grassland	(specify)															
	(specify)															
…..																

(1) Land categories may be further divided according to climate zone, management system, soil type, vegetation type, tree species, ecological zones, national land classification or other criteria.

(2) The signs for estimates of increases in carbon stocks are positive (+) and of decreases in carbon stocks are negative (-).

(3) According to IPCC Guidelines, changes in carbon stocks are converted to CO_2 by multiplying C by 44/12 and changing the sign for net CO_2 removals to be negative (-) and for net CO_2 emissions to be positive (+).

Documentation box:

Use this documentation box to provide references to relevant sections of the Inventory Report if any additional information and/or further details are needed to understand the content of this table.

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To ensure the completeness of an inventory, it is good practice to fill in information for all entries of the table. If actual emission and removal quantities have not been estimated or cannot otherwise be reported in the tables, the inventory compiler should use the following qualitative "notation keys" (from IPCC 2006 GL) and provide supporting documentation.

Notation key	Explanation
NE (Not estimated)	Emissions and/or removals occur but have not been estimated or reported.
IE (Included elsewhere)	Emissions and/or removals for this activity or category are estimated but included elsewhere. In this case, where they are located should be indicated,
C (Confidential information)	Emissions and/or removals are aggregated and included elsewhere in the inventory because reporting at a disaggregated level could lead to the disclosure of confidential information.
NA (Not Applicable)	The activity or category exists but relevant emissions and removals are considered never to occur.
NO (Not Occurring)	An activity or process does not exist within a country.

For example, if a country decides that a disproportionate amount of effort would be required to collect data for a pool from a specific category that is not a key category (see Ch. 4) in terms of the overall level and trend in national emission, then the country should list all gases/pools excluded on these grounds, together with a justification for exclusion, and use the notation key 'NE' in the reporting tables.

Furthermore, the reporting tables are generally complemented by a documentation box which should be used to provide references to relevant sections of the Inventory Report if any additional information is needed.

In addition to tables like those illustrated in Box 6-1, other typical tables to be filled in a comprehensive GHG inventory include:

- Tables with emissions from other gases (e.g., CH_4 and N_2O from biomass burning), to be expressed both in unit of mass and in CO_2 equivalent (using the Global Warming Potential of each gas provided by the IPCC)
- Summary tables (with all the gases and all the emissions/removals)
- Tables with emission trends (covering data also from previous submissions)
- Tables for illustrating the results of the key category analysis, the completeness of the reporting, and eventual recalculations.

In the context of REDD, most of these types of tables will likely need to be completed for the reference period and for the assessment period, although it is not yet clear if non-CO_2 gases and all pools will be required.

Inventory Report: The other part of a national inventory is an Inventory Report that contains comprehensive and transparent information about the inventory, including:

- An overview of trends for aggregated GHG emissions, by gas and by category.
- A description of the methodologies used in compiling the inventory, the assumptions, the data sources and rationale for their selection, and an indication

of the level of complexity (IPCC tiers) applied. In the context of REDD reporting, appropriate information on land-use definitions, land area representation and land-use databases are likely to be required.

- A description of the key categories, including information on the level of category disaggregation used and its rationale, the methodology used for identifying key categories, and if necessary, explanations for why the IPCC-recommended Tiers have not been applied.
- Information on uncertainties (i.e., methods used and underlying assumptions), time-series consistency, recalculations (with justification for providing new estimates), quality assurance and quality control procedures.
- A description of the institutional arrangements for inventory preparation.
- Information on planned improvements.

Furthermore, all of the relevant inventory information should be compiled and archived, including all disaggregated emission factors, activity data and documentation on how these factors and data were generated and aggregated for reporting. This information should allow, inter alia, reconstruction of the inventory by the expert review teams.

6.3 What are the major challenges for developing countries?

Although the inventory requirements for a REDD mechanism have not yet been designed, it is possible to foresee some of the major challenges that developing countries will encounter in estimating and reporting emissions from deforestation and forest degradation. In particular, what difficulties can be expected if the five principles outlined above are required for REDD reporting?

While specific countries may encounter difficulties in meeting transparency, consistency and comparability principles, it is likely that most countries will be able to fulfill these principles reasonably well after adequate capacity building. In contrast, based on the current monitoring and reporting capabilities, the principles of completeness and accuracy will likely represent major challenges for most developing countries, especially for estimating emissions of the reference period.

Achieving the *completeness* principle will clearly depend on the processes (e.g. deforestation, forest degradation) involved, the pools and gases that needed to be reported, and the forest-related definitions that are applied. For example, evidence from official reports (e.g., NAI national communications to UNFCCC[37], FAO's FRA 2005[38]) suggests that only a very small fraction of developing countries currently reports data on soil carbon, even though emissions from soils following deforestation are likely to be significant in many cases.

If *accurate* estimates of emissions are to be reported, reliable methodologies are needed as well as a quantification of their uncertainties. For key categories and significant pools, this implies the application of higher tiers, i.e. having country-specific data on all the significant pools stratified by climate, forest, soil and conversion type at a fine to medium spatial scale. Although adequate methods exist (as outlined in the previous chapters of the sourcebook), and the capacity for monitoring emissions from deforestation is improving, in many developing countries accurate data on deforested areas and carbon stocks are still scarce and allocating significant extra resources for monitoring may be difficult in the near future.

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[37] UNFCCC. 2005. Sixth compilation and synthesis of initial national communications from Parties not included in Annex I to the Convention. FCCC/SBI/2005/18/Add.2

[38] Food and Agriculture Organization. 2006. Global Forest Resources Assessment.

In this context, how could the obstacle of potentially incomplete and highly uncertain REDD reporting be overcome?

6.4 The conservativeness approach

To address the potential incompleteness and the uncertainties of REDD estimates, and thus to increase their credibility, it has been proposed to use the approach of "conservativeness".

In the REDD context, conservativeness means that - when completeness or accuracy of estimates cannot be achieved - the reduction of emissions should not be overestimated, or at least the risk of overestimation should be minimized.

Although this approach may appear new to some, it is already present in the UNFCCC context, even if somehow "hidden" in technical documents. For example, the procedure for adjustments under Art 5.2 of the Kyoto Protocol works as follows [39]: if an AI Party reports to UNFCCC emissions or removals in a manner that is not consistent with IPCC methodologies and would give benefit for the Party, e.g. an overestimation of sinks or underestimation of emissions in a given year of the commitment period, then this would likely trigger an "adjustment", i.e., a change applied by an independent expert review team (ERT) to the Party's reported estimates. In this procedure, the ERT may first substitute the original estimate with a new one (generally based on a default IPCC estimate, i.e. a Tier 1) and then - given the high uncertainty of this new estimate - multiply it by a tabulated category-specific "conservativeness factor" (see Figure 6.1). Differences in conservativeness factors between categories reflect typical differences in total uncertainties, and thus conservativeness factors have a higher impact for categories or components that are expected to be more uncertain (based on the uncertainty ranges of IPCC default values or on expert judgment). In this way, the conservativeness factor acts to decrease the risk of underestimating emissions or overestimating removals in the commitment period. In the case of the base year, the opposite applies. In other words, the conservativeness factor may increase the "quality" of an estimate, e.g. decreasing the high "risk" of a Tier 1 estimate up to a level typical of a Tier 3 estimate. Of course, the extent of the correction depends also on the level of the confidence interval[40]: for example, by taking the lower bound of the 50% or 95% confidence interval means, respectively, having 25% or 2.5% probability of overestimating the "true" value of the emissions (in case of Art. 5.2 of the Kyoto Protocol the 50% confidence interval is used). By contrast, by taking the mean value (and assuming a normal distribution) there is an equal chance (50%) for over- and under-estimation of the true value.

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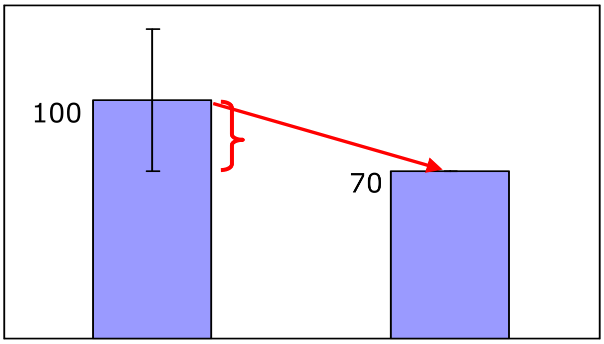
[39] UNFCCC 2006. Good practice guidance and adjustments under Article 5, paragraph 2, of the Kyoto Protocol FCCC/KP/CMP/2005/8/Add.3 Decision 20/CMP.1

[40] The confidence interval is a range that encloses the true (but unknown) value with a specified confidence (probability). E.g., the 95 % confidence interval has a 95% probability of enclosing the true value.

Figure 6.1. Conceptual example of the application of a conservativeness factor during the adjustment procedure under Art. 5.2 of the Kyoto Protocol. The bracket indicates the risk of overestimating the true value, which is high if, for example, a Tier 1 estimate is used. Multiplying this estimate by a conservativeness factor (in this case 0.7), derived from category-specific tabulated confidence intervals, means decreasing the risk of overestimating the true value.



Another example comes from the modalities for afforestation and reforestation project activities under the Clean Development Mechanism (CDM)[41], which prescribes that "the baseline shall be established in a transparent and conservative manner regarding the choice of approaches, assumptions, methodologies, parameters, data sources, …and taking into account uncertainty".

Furthermore, the concept of conservativeness is *implicitly* present also elsewhere. For example, the Marrakech Accords specify that, under Articles 3.3 and 3.4 of the Kyoto Protocol, Annex I Parties "may choose not to account for a given pool if transparent and verifiable information is provided that the pool is not a source", which means applying conservativeness to an incomplete estimate. In addition, the IPCC GPG-LULUCF (2003) indicates the use of the Reliable Minimum Estimate (Chapter 4.3.3.4.1) as a tool to assess changes in soil carbon, which means applying conservativeness to an uncertain estimate.

Very recently, this concept entered also in the text of ongoing REDD negotiations[42], where among the methodological issues identified for further consideration it was included "*Means to deal with uncertainties in estimates aiming to ensure that reductions in emissions or increases in removals are not over-estimated*".

However, although the usefulness of the conservativeness concept seems largely accepted, its application in the REDD context clearly needs some guidance. In other words: how to implement, in practice, the conservativeness approach to the REDD context? To this aim, the next two sections show some examples on how the conservativeness approach may be applied to a REDD mechanism when estimates are incomplete or uncertain, respectively.

6.4.1 Addressing incomplete estimates

It is likely that a typical and important example of incomplete estimates will arise from the lack of reliable data for a carbon pool, and especially the soil pool. In this case, being conservative in a REDD context does not mean "not overestimating the emissions", but

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[41] UNFCCC 2006. Modalities and procedures for afforestation and reforestation project activities under the clean development mechanism in the first commitment period of the Kyoto Protocol Decision 5/CMP.1

[42] http://unfccc.int/resource/docs/2008/sbsta/eng/l12.pdf

rather "not overestimating the reduction of emissions". If soil is not accounted for, the total emissions from deforestation will very likely be underestimated in both periods. However, assuming for the most disaggregated reported level (e.g., a forest type converted to cropland) the same emission factor (C stock change/ha) in the two periods, and provided that the area deforested is reduced from the reference to the assessment period, also the reduced emissions will be underestimated. In other words, although neglecting soil carbon will cause a REDD estimate which is not complete, this estimate will be conservative (see Table 6.1) and therefore should not be considered a problem. However, this assumption of conservative omission of a pool is *not* valid anymore if, for a given forest conversion type, the area deforested is increased from the reference to the assessment period; in such case, any pool which is a source should be estimated and reported.

Table 6.1: Simplified example of how ignoring a carbon pool may produce a conservative estimate of reduced emissions from deforestation. The reference level might be assessed on the basis of historical emissions. (a) complete estimate, including the soil pool; (b) incomplete estimate, as the soil pool is missing. The latter estimate of reduced emissions is not accurate, but is conservative.

	Area deforested (ha x 10^3)	Carbon stock change (t C/ha deforested)		Emissions (area deforested x C stock change, t C x 10^3)	
		Above-ground Biomass	Soil	Aboveground Biomass + Soil	Only Above-ground Biomass
Reference level	10	100	50	1500	1000
Assessment period	5	100	50	750	500
Reduction of emissions (reference level - assessment period, t C x 10^3)				**750** (a)	**500** (b)

6.4.2 Addressing uncertain estimates

Assuming that during the "estimation phase" the Party carries out all the practical efforts to produce accurate and precise REDD estimates (i.e., to reduce uncertainties), as well as to quantify the uncertainties according to the IPCC guidance, here we suggest a simple approach to deal with at least part of the remaining uncertainties.

Similarly to the adjustment procedure under Art. 5.2 of the Kyoto Protocol (see before), we propose to use the confidence interval in a conservative way, i.e. to decrease the probability of producing an error in the unwanted direction. Specifically, here we briefly present two possible approaches to implement this concept:

Approach A): the conservative estimate of REDD is derived from the uncertainties of both the reference and the assessment periods. Following the idea of the Reliable Minimum Estimate (IPCC GPG LULUCF 2003), the aim is to decrease both the risk of overestimating the emissions in reference period and the risk of underestimating the emissions in the assessment period. Therefore, this approach calculates the difference between the lower bound of the confidence interval (i.e., downward correction) of emissions in the reference period and the higher bound of the confidence interval (i.e., upward correction) of emissions in the assessment period (see Fig. 6.2A).

Approach B): the conservative estimate of REDD is derived from the uncertainty of the difference of emissions between the reference and the assessment period (uncertainty of the trend, IPCC 2006 GL, as illustrated in Fig. 6.2B). From a conceptual point of view, this approach appears more appropriate than approach A for the REDD context, since the emission reduction (and the associated trend uncertainty) is more important that the absolute level of uncertainty of emissions in the reference and assessment period. A peculiarity of the uncertainty in the trend is that it is extremely dependent on whether uncertainties of inputs data (Activity Data, AD, and Emission Factor, EF) are correlated or not between the reference and the assessment period. In particular, if the uncertainty is correlated between periods it does not affect the % uncertainty of the trend. In uncertainty analyses of GHG inventories, no correlation is typically assumed for activity data in different years, and a perfect positive correlation between emission factors is assumed in different years. This is the basic assumption given by the IPCC (IPCC 2006 GL), which we consider fully valid also in the REDD context.

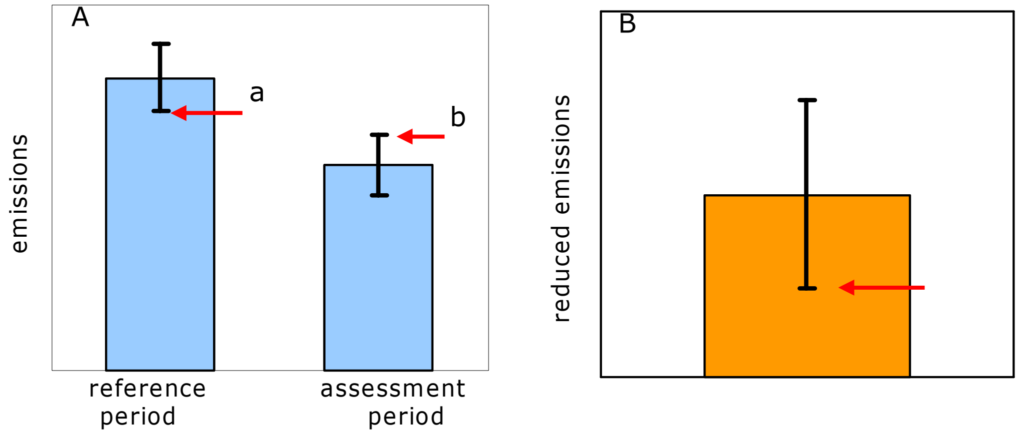


Figure 6.2. With approach A (left), the conservative estimate of REDD is calculated based on the uncertainties of both the reference and the assessment period (a - b). With approach B (right), the conservative estimate of REDD is derived from the uncertainty of the difference of emissions between the reference and the assessment period (uncertainty of the trend). For further details see Box 6.2.

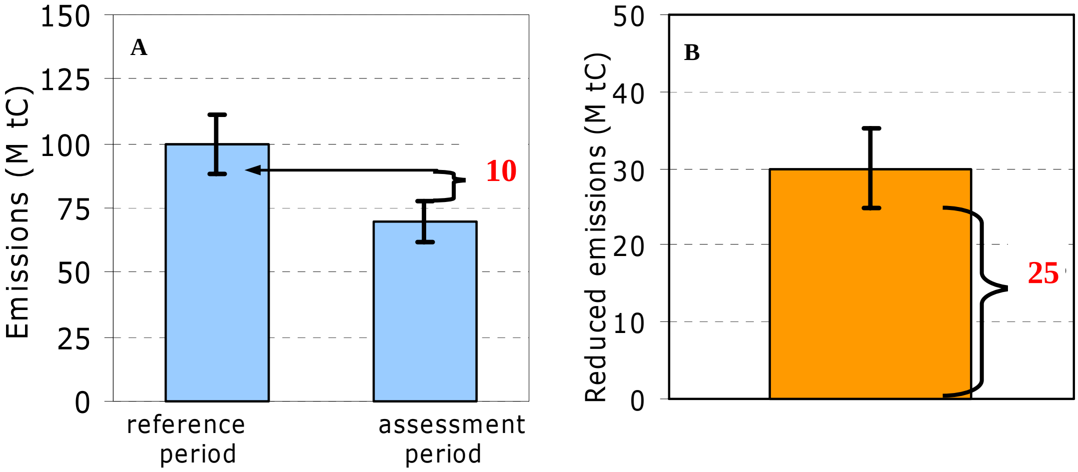
In Box 6.2 an example of the application of the two approaches is briefly illustrated.

Our proposal of correcting conservatively the REDD estimates may be based on the uncertainties quantified by the country when estimated in a robust way (that will be subject to subsequent review). In absence of such estimates from the country, the confidence intervals may be derived from tabulated category-specific uncertainties, possibly produced by the IPCC or other independent bodies (as in the case of Art. 5.2 of the Kyoto Protocol).

In any case, during the review phase, the reported AD and EF will be analyzed. If the review concludes that the methodology used is not consistent with recommended guidelines by IPCC or with the UNFCCC's principles, and may produce overestimated REDD data, the problem could be addressed by applying a default factor multiplied by a conservative factor (as already described for Art. 5.2 under the Kyoto Protocol).

BOX 6.2: Simulating two approaches for treating uncertainties in a conservative way.

The figure below shows an example of a result of the two approaches described in Section 6.4.2. It clearly emerges that by using approach A only limited reductions of emissions from deforestation could be conservatively demonstrated (number close to bracket), unless a large a reduction of deforestation occurred or uncertainties in inputs data are very low. By contrast, approach B (using the uncertainty of the trend) produces only a small reduction of original non-conservative estimate. This difference is due to the fact that uncertainty of emission factor (EF) is irrelevant for % uncertainty of the trend in approach B. However, it should be noted that the fact that the uncertainty of EF is irrelevant for % uncertainty of the trend does not undermine the importance of using accurate EF: indeed, the absolute value of the EF will of course affect the absolute value of the REDD estimates, irrespective of its uncertainty. The correctness of the absolute value of EF will likely be analyzed during the review phase, by independent experts.



Application of conservativeness approaches A (left panel) and B (right panel) to the following exemplificative scenario:

- Activity Data (deforestation rate): 1.0 M ha/yr in the reference period, 0.7 M ha/yr in the assessment period.

- Emission Factor: 100 tC/ha of deforested area, in both the reference and the assessment period.

- Estimated reduction of emissions: 30 M tC/yr.

- Level of uncertainty in input data: 15% for activity data, 30% for emission factor.

Red numbers close to brackets represent the conservative estimates assessed at the 50% confidence interval. Obviously, the level of the confidence interval used greatly affects the results of the simulations. The example below uses the 50% because it is the one used under Art. 5.2 of the Kyoto Protocol. The closer to 100% is this level the higher is the credibility of the estimates (i.e. the lower is the risk of overestimating REDD), but also the higher is risk to discourage the implementation of REDD mechanism by developing countries.

6.4.3. Conservativeness as a win-win option

REDD estimates should be complete, accurate and precise. However, once the Party has carried out all the practical efforts in this direction, *uncertainties should be dealt to ensure that reductions in emissions or increases in removals are not over-estimated*. To this aim, in Ch. 6.4.1 and 6.4.2 we proposed few examples of how the conservativeness approach can be applied to an incomplete estimate (e.g., an omission of a pool) and to an uncertain estimate. In the REDD context, the conservativeness approach has the following advantages:

- Increases the scientific robustness, the environmental integrity and the credibility of any REDD mechanism. By decreasing the risk that economic incentives are given to undemonstrated reductions of emission, the credibility of any REDD mechanism becomes less constrained by the level of accuracy of the estimates. This should help convincing policymakers, investors and NGOs in industrialized countries that a robust and credible reporting of REDD estimates is possible.

- Rewards the quality of the estimates. Indeed, more accurate/precise estimates of deforestation, or a more complete coverage of C pool (e.g., including soil), will likely translate in higher REDD estimates, thus allowing to claim for more incentives. Thus, if a REDD mechanism starts with conservativeness, precision and accuracy will likely follow.

- Allows flexible monitoring requirements: since the quality of the estimates is rewarded, it could be envisaged a system in which - provided that conservativeness is satisfied, - Parties are allowed to choose themselves what pool to estimate and at which level of accuracy/precision (i.e. Tier), depending on their own cost-benefit analysis and national circumstances.

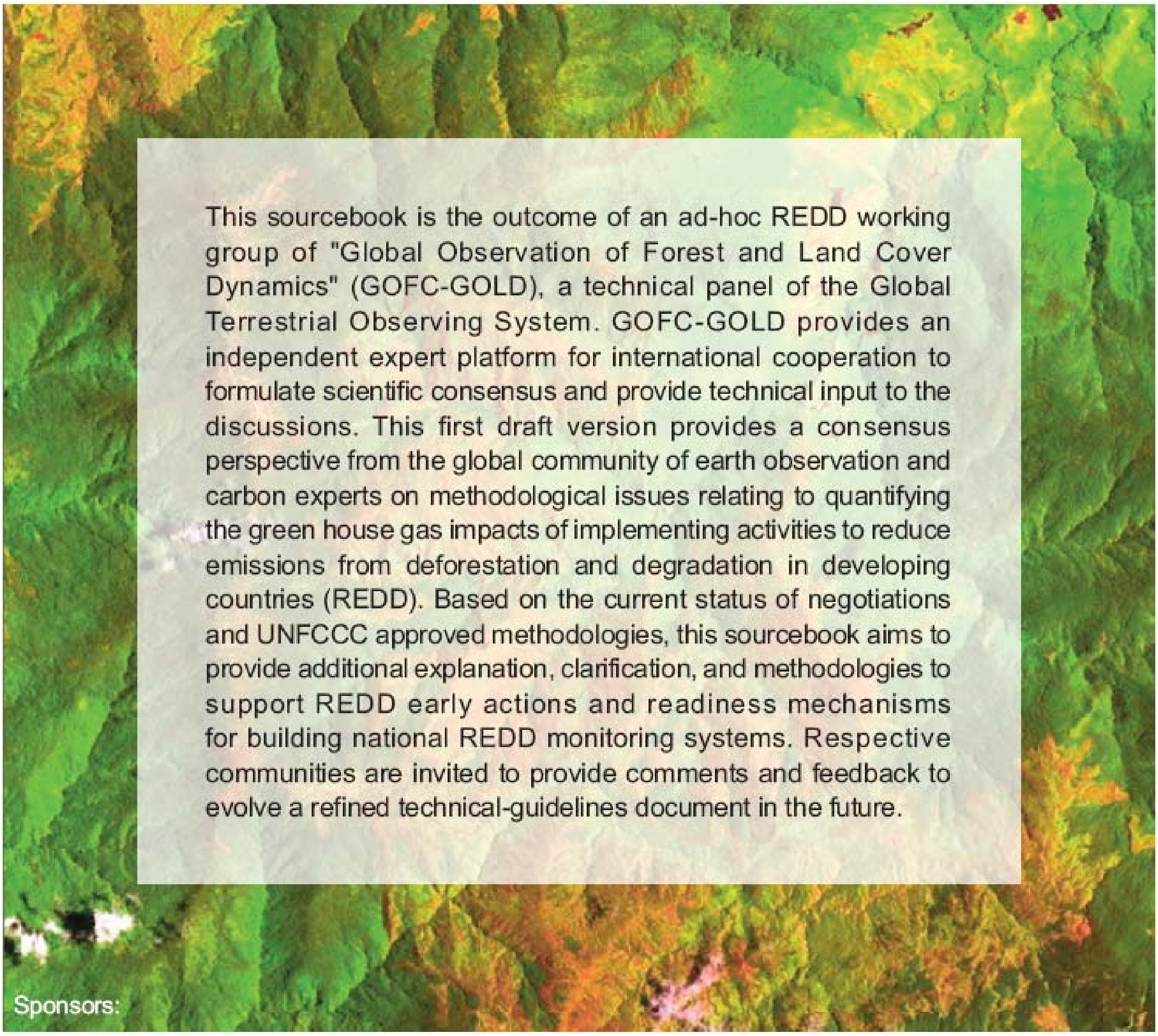
- Stimulates a broader participation, i.e. allows developing countries to join the REDD mechanism even if they cannot provide accurate/precise estimates for all carbon pools or key categories, and thus decreases the risk of emission displacement from one country to another.

- Increases the comparability of estimates across countries – a fundamental UNFCCC reporting principle - and also the fairness of the distribution of eventual positive incentives.

6.5 References of chapter 6

Grassi G, Monni S, Federici S, Achard F, Mollicone D (2008): From uncertain data to credible numbers: applying the conservativeness principle to REDD. *Environ. Res. Lett.*, submitted.

Mollicone D, Freibauer A, Schulze E-D, Braatz S, Grassi G, Federici S (2007): Elements for the expected mechanisms on Reduced Emissions from Deforestation and Degradation (REDD) under UNFCCC. *Environ. Res. Lett*. **2** 045024



This sourcebook is the outcome of an ad-hoc REDD working group of "Global Observation of Forest and Land Cover Dynamics" (GOFC-GOLD), a technical panel of the Global Terrestrial Observing System. GOFC-GOLD provides an independent expert platform for international cooperation to formulate scientific consensus and provide technical input to the discussions. This first draft version provides a consensus perspective from the global community of earth observation and carbon experts on methodological issues relating to quantifying the green house gas impacts of implementing activities to reduce emissions from deforestation and degradation in developing countries (REDD). Based on the current status of negotiations and UNFCCC approved methodologies, this sourcebook aims to provide additional explanation, clarification, and methodologies to support REDD early actions and readiness mechanisms for building national REDD monitoring systems. Respective communities are invited to provide comments and feedback to evolve a refined technical-guidelines document in the future.

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