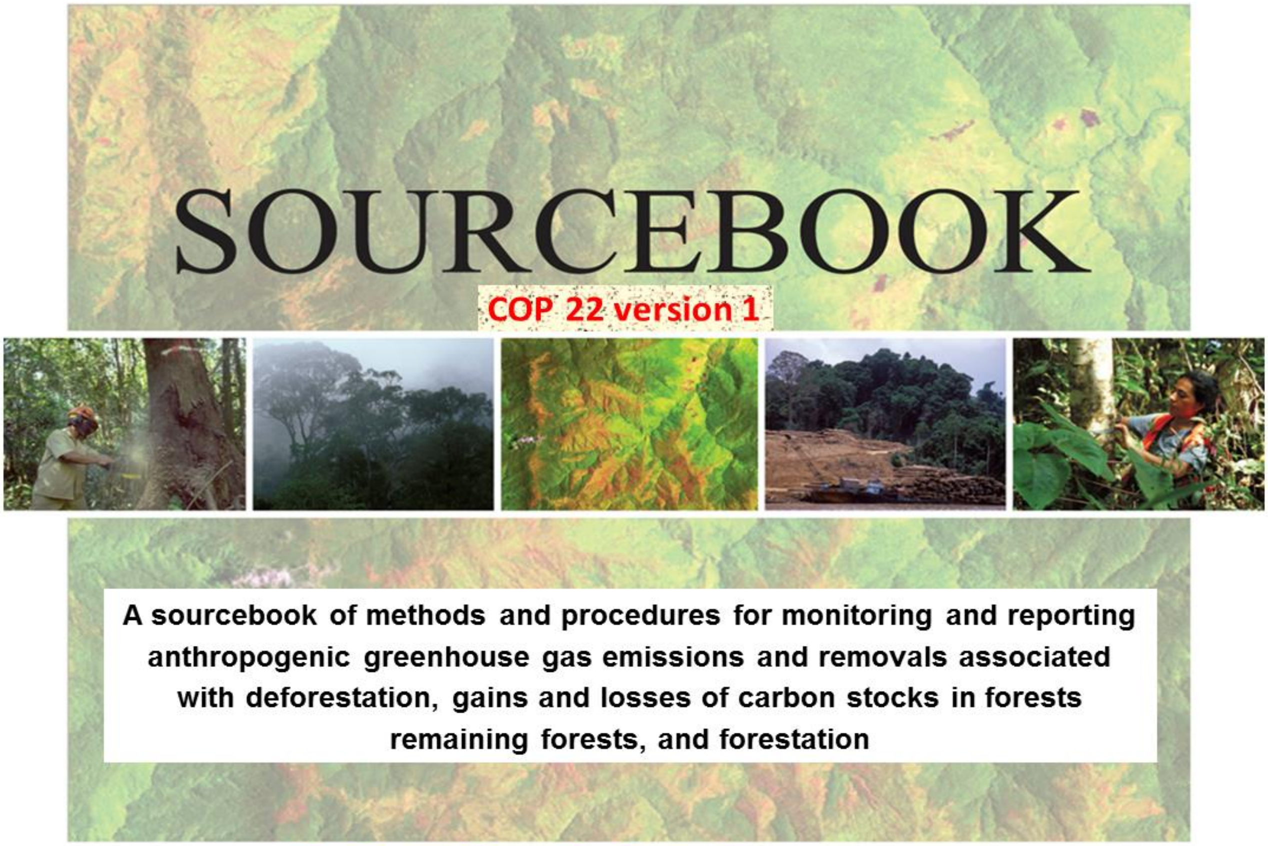

SOURCEBOOK

COP 22 version 1

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

GOFC-GOLD

Global Observation of Forest and Land Cover Dynamics

A SOURCEBOOK OF METHODS AND PROCEDURES FOR MONITORING AND REPORTING ANTHROPOGENIC GREENHOUSE GAS EMISSIONS AND REMOVALS ASSOCIATED WITH DEFORESTATION, GAINS AND LOSSES OF CARBON STOCKS IN FORESTS REMAINING FORESTS, AND FORESTATION

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 greenhouse gas (GHG) impacts of implementing mitigation activities related to the forest land use in developing countries (REDD+). Currently the climate negotiations identify five forest-related REDD+ activities as mitigation actions by developing countries, namely: reducing emissions from deforestation (which implies a land-use change) and reducing emissions from forest degradation, conservation of forest carbon stocks, sustainable management of forest land, enhancement of forest carbon stocks (all relating to carbon stock changes and GHG emissions within managed forest land use). Enhancement of forest carbon stocks could also entail land use change, if achieved by afforestation or reforestation. Based on the current status of negotiations and UNFCCC approved methodologies, the Sourcebook aims to provide additional explanation, clarification, and methodologies to support REDD+ early actions and readiness mechanisms for building national REDD+ monitoring systems. It complements the Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines for National Greenhouse Gas Inventories[1] and it aims at being fully consistent with this IPCC Guidelines and with the UNFCCC reporting guidelines on annual GHG inventories. The sourcebook emphasizes the role of satellite remote sensing as an important tool for monitoring changes in forest cover, provides guidance on how to obtain credible estimates of forest carbon stocks and related changes, and provides clarification on the use of IPCC Guidelines for estimating and reporting GHG emissions and removals from forest lands. GOFC-GOLD is represented on Advisory and Author Groups responsible for the production of the Methods and Guidance Document (MGD) of the Global Forest Observations Initiative (GFOI)[2]. The MGD provides operational advice on applying IPCC Guidance to REDD+ activities and is complementary to the Sourcebook.

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, carbon measurement and reporting under the UNFCCC have contributed to the development of this sourcebook.

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[1] The 2006 Guidelines are the most recent from the IPCC. COP17 decided that the IPCC 1996 Guidelines, in conjunction with the 2000 and 2003 Good Practice Guidance would be used by developing countries for estimating greenhouse gas emissions and removals (see FCCC/CP/2011/9/Add.1, page 40). This Sourcebook assumes that countries will wish to use the updated information in the IPCC 2006 Guidelines as scientific input to their emissions and removals estimates made using the guidance agreed by COP17.

[2] http://www.gfoi.org/methods-guidance-documentation

The 19th Conference of Parties (COP) to the UNFCCC took place in Warsaw in November 2013 and agreed seven decisions (9/CP.19 to 15/CP19 inclusive) on REDD+. These are known collectively as the *Warsaw Framework on REDD+.* They reference decisions previously adopted, including 4/CP.15, 1/CP.16, and 12/CP.17. Agreeing the Warsaw Framework is an important achievement. Four[3] of the Warsaw decisions refer to subjects discussed in the Sourcebook, which amongst other things provides a reference point to support estimation of emissions and removals associated with REDD+ activities, the development of national forest monitoring systems (both 11/CP.19) and forest reference emission levels and forest reference levels (13/CP.19 and 12/CP.17). This sourcebook is a living document and further methods and technical details can be specified and added with evolving negotiations and science. Respective communities are invited to provide comments and feedback to evolve a more detailed and refined guidelines document in the future.

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[3] Namely 11/CP.19 (Modalities for National Forest Monitoring Systems); 13/CP.19 (Guidelines and procedures for the technical assessment of submissions from Parties on proposed forest reference emission levels and/or forest reference levels); 14/CP.19 (Modalities for measuring, reporting and verifying); 15/CP.19 (Addressing the drivers of deforestation and forest degradation).

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In addition to the core editors, a number of international experts in remote sensing, carbon measurement and accounting have contributed to the development of the Sourcebook and are thankfully acknowledged for their support. This Sourcebook is the result of a joint voluntary effort from more than 30 contributing authors 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 section(s) to which they contributed and immediately below in alphabetical order:

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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). The second version was distributed at the UNFCCC Workshop on Methodological Issues relating to REDD+ held in Tokyo (June 2008). The third and fourth versions were published in 2009 for the COP 15. The fifth version for COP 16 in November 2010 addresses REDD+ Plus issues and includes a series of sections providing practical examples for data collection, India study case, community-based measurements and recommendations for country capacity building. The sixth and seventh versions for COP 17 and COP 18 held in November 2011 and November 2012 include significantly updated sections in relation to decisions adopted at COP 16 (Decision 1/CP.16) and at COP 17 (Decisions 1/CP.17 and 12/CP.17).

We acknowledge the following people for the comments which were made on earlier versions of the Sourcebook: Albert Ackhurst, Sharon Gomez, Steven De Gryze, Doug Muchoney, Jeffrey Himel and Bill Stanley. We thank Nandinerdene Tsendbazar for her editing work.

What’s new in this version?

Information in section 2.9 **guidance on reporting** is updated notably to take into account the Paris Agreement. Section 2.1 on **monitoring changes in forest area** has been updated, notably with a section on the use of **global products** that refers to the guidance provided by the Global Forest Observations Initiative (GFOI). Section 2.10 on evolving technologies now provides updated information on the use of **allometric models constructed from samples of biomass**. The sub-section on **LIDAR** has been updated also. Typos, layout issues, and misspellings were corrected throughout the document.

Table of Contents

1 INTRODUCTION

1.1 PURPOSE AND SCOPE OF THE SOURCEBOOK

This sourcebook is designed to assist in i) estimation of emissions and removals associated with REDD+ activities, ii) design of national forest monitoring systems (NFMS), iii) assessment of historical data for reference emission level (REL) and reference levels (RL). The sourcebook is based on the general reporting requirements set by the United Nations Framework Convention on Climate Change (UNFCCC) and the specific methodologies for the Agriculture, Forestry and Other Land Use (AFOLU) sector provided by the Intergovernmental Panel on Climate Change (IPCC).

The sourcebook introduces users to: i) key issues and challenges related to monitoring and estimating carbon stock changes and non-CO_2 emissions from deforestation and management of forest land; ii) methods provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for Agriculture, Forestry and Other Land Use (GL-AFOLU); iii) how these IPCC methods provide the steps needed to estimate carbon stock changes and non-CO_2 emissions iv) issues and challenges related to reporting under the UNFCCC.

The sourcebook identifies transparent methods that are designed to produce accurate estimates of changes in forest area and carbon stocks and non-CO_2 emissions from deforestation and management of forest land, in a format that is user-friendly. It is intended to complement the IPCC AFOLU Guidelines and other relevant advice including particularly the Methods and Guidance document published in January 2014 by the Global Forest Observations Initiative[4]. The Sourcebook provides an annually updated review of relevant science and the MGD gives step-by-step advice on how each REDD+ activity can estimated in a readily implementable way using IPCC methods. The Sourcebook and the MGD can be used together to provide estimates of REDD+ activities consistent with IPCC Guidance as required by the UNFCCC COP[5].

The sourcebook is not a primer on how to analyze remote sensing data nor how to collect field measurements of forest carbon stocks. 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: Monitoring systems 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: Systems meet international requirements, be implemented at the national level, and with approaches that have potential for representing sub-national activities.
- Consistency: Proposed methods/activities shall be consistent with IPCC methods and with current provisions on reporting under the UNFCCC.

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[4] http://www.gfoi.org/methods-guidance-documentation

[5] For more information on the use of the Sourcebook and the MGD see http://gfoi.org/mgd-modules

- ☐ Efficiency: Proposed methods should allow cost-effective and timely implementation, and support early actions.
- ☐ Robustness: Monitoring should provide appropriate results based on sound scientific underpinning and international technical consensus among expert groups.
- ☐ Transparency: The system should be open and readily available for independent reviewers and the methodology should be replicable.

1.2 UNFCCC CONTEXT AND REQUIREMENTS

Permanent conversion of forested to non-forested areas in developing countries has caused significant accumulation of greenhouse gases in the atmosphere, as have forest degradation caused by high impact logging, over-exploitation for fuel wood, intense grazing that reduces regeneration, and fires. IPCC's 5th Assessment Report indicates that about 25% of anthropogenic emissions are from agriculture, forests and other land use (AFOLU) of which about half are from deforestation, forest degradation and peat decay and fires. Annual Carbon emissions from tropical deforestation and degradation during the 2000s accounted for about 10-20% of the total anthropogenic emissions of greenhouse gases[6].

Mainly because of risk of displacement, forest activities other than afforestation and reforestation in developing countries are not eligible for the clean development mechanism (CDM). However, since 2005 the possibility of national reference levels (with concomitant reduction of displacement risk) led to consideration of REDD+ as part of a future climate agreement, and the 19th Conference of Parties in November 2013 agreed the seven decisions comprising the Warsaw Framework for REDD+. The Warsaw Framework refers to previous decisions of the COP which identify IPCC methodologies and UNFCCC reporting principles as the basis for REDD+ and requires … *data and information that are transparent, consistent over time and are suitable for measuring, reporting and verifying…*[7]

1.2.1 LULUCF in the UNFCCC and Kyoto Protocol

To understand the assessment of the forest related emissions and removals under the Convention and through the application of the IPCC methodologies it is useful to consider the arrangements for the LULUCF sector for the developed countries under the Convention and the Kyoto Protocol.

Under the current rules for Annex I Parties (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 differ between the UNFCCC and the Kyoto Protocol (Table 1.2.1). Although Convention reporting includes all emissions/removals from LULUCF, under the Kyoto Protocol the reporting and accounting of emissions/removals for the second commitment period, is mandatory only for the activities under Art. 3.3 and for forest management under Art. 3.4. Other activities under Art. 3.4 are voluntary (see Table 1.2.1). In addition under the KP developed counties may implement afforestation and reforestation projects in developing countries. For the national inventories, estimating and reporting guidelines can be drawn from

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[6] http://www.ipcc.ch/report/ar5/wg1/

[7] See decision 11/CP.19 (Modalities for national forest monitoring systems)

UNFCCC documents[8] and the IPCC 2006 Guidelines in which the Agriculture and LULUCF sectors are integrated to form the Agriculture, Forestry and Other Land Use (AFOLU) sector. The IPCC 2006 Guidelines were adopted by COP 17 for Annex-I Parties for reporting under UNFCCC[9]. Annex 3 of decision 2/CP.17 specifies that non-Annex 1 Parties should use the Revised 1996 IPCC Guidelines in conjunction with the IPCC Good Practice Guidance of 2000 and 2003 (which covers Land Use, Land-Use Change and Forestry), and encourages use of the reporting tables annexed to the 2003 GPG for LULUCF. In this sourcebook we make reference to the 2006 guidelines (as GL-AFOLU) because they represent the most relevant and updated source of methodological information[10] and can be used by countries as background information consistent with IPCC GPG for LULUCF.

Table 1.2.1. Existing frameworks for the Land Use, Land Use Change and Forestry (LULUCF) sector under the UNFCCC and the second commitment period of 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 land Cropland Grassland Wetlands Settlements Other Land	**Article 3.3** Afforestation/Reforestation, Deforestation since 1990 **Article 3.4 mandatory** Forest management **Article 3.4 elective** Cropland management Grazing land management Forest management Revegetation Wetland drainage and rewetting	**CDM** Afforestation/ Reforestation

1.2.2 Definition of forests, deforestation and degradation

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

[9] Decision 15/CP.17 FCCC/CP/2011/9/Add.2

[10] Decision 12/CP.17 on REDD+ Safeguards and reference levels indicates that non-Annex I Party "aiming to undertake the actions listed in decision 1/CP.16, paragraph 70, should include in its submission transparent, complete, consistent with guidance agreed by the COP, and accurate information for the purpose of allowing a technical assessment of the data, methodologies and procedures used in the construction of a forest reference emission level and/or forest reference level. The information provided should be guided by the most recent IPCC guidance and guidelines, as adopted or encouraged by the COP, as appropriate".

For REDD+ activities many terms, definitions and other elements are not formally defined (e.g. terms 'deforestation' and 'forest degradation') and can vary between countries. As decisions for REDD+ will probably build on the current modalities under the UNFCCC and the Kyoto Protocol, current definitions and terms represent a starting point for considering refined and/or additional definitions, if 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. In general for reporting under the UNFCCC only generic definitions on land uses are used, but Kyoto Protocol reporting prescribes a set of definitions to be applied for LULUCF activities, although some flexibility is still 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. Moreover, the contemporary presence of other uses which may be predominant should be taken into account[11].

The estimation of deforestation is affected by the definitions of 'forest' versus 'non-forest' land 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 2010, the FAO[12] uses a minimum cover of 10%, height of 5m and area of 0.5ha stating also that forest use should be the predominant use. 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[13], Parties select a single value of crown area, tree height and area to define forests within their national boundaries. Selection is from within the 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 %

With 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 change in the forest cover not followed by a change in use, 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 developing 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 forest 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

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[11] The presence of a predominant forest-use is crucial for land use classification since the mere presence of trees is not enough to classify an area as forest land (e.g. an urban park with trees exceeding forest threshold should not be considered as a forest land).

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

[13] Decision 16/CMP.1 http://unfccc.int/resource/docs/2005/cmp1/eng/08a03.pdf#page=3

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 16/CMP.1, 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 use and usually in land cover. Common changes include: conversion of forests to annual cropland, conversion to pasturelands, conversion to perennial plants (oil palm, shrubs), and conversion to urban lands or other human infrastructure.

Forest degradation and enhancement of carbon stocks within forest land – In forest areas where there are anthropogenic net emissions (i.e. where GHG emissions are larger than removals), during a given time period (no longer than the commitment period of the accounting framework) with a resulting decrease in canopy cover/biomass density that does not qualify as deforestation, are classified as subject to forest degradation.

The IPCC 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 direct human-induced/anthropogenic decrease in carbon stocks, with measured canopy cover remaining above the threshold for definition of forest and no change in land use. Moreover, to be distinguished from forestry activities the decrease should be considered persistent. The persistence could be evaluated by monitoring carbon stock changes either over time (i.e. a net decrease during a given period, e.g. 20 years) or along space (e.g. a net decrease over a large area where all the successional stages of a managed forest are present).

Considering that, at national level, sustainable forest management leads to national gross losses of carbon stocks (e.g. through harvesting) which can be only lower than (or equal to) national gross gains (in particular through forest growth), consequently a net decrease of forest carbon stocks at national level during a reporting period would be due to forest degradation within the country. Conversely, a net increase of forest carbon stocks at national level would correspond to forest enhancement.

In practice it is likely to be difficult to agree the values for X, Y and T and doing so has the disadvantage of introducing a possible incentive to degrade to just above the threshold values. Therefore, it is also possible that no specific definition is needed, and that any "degradation of forest" will be reported simply as a net decrease of carbon stock in the category "Forest land remaining forest land" at national or sub-national level. The GFOI Methods and Guidance Document[14] does not attempt to formally to define degradation, but it does set out steps for estimating degradation using IPCC methods. These are based on transitions from undisturbed or less disturbed forest strata, plus long term trends in carbon density of disturbed strata. The MGD also recognizes that non-carbon forest values may mean that lower carbon density forest are not counted as degraded, but in this case clearly the reduction in carbon stocks should be estimated under a sustainable activity.

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. However, a time series of national forest inventories can properly identify and quantify, with high accuracy, changes in forest covers and related carbon stocks.

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 net 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 2.2). 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 "forest land remaining forest land".
- ☐ 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. Practically all fires in tropical forests have anthropogenic causes, 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.

1.2.3 General method for estimating CO_2 emissions and removals

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[14] See MGD section 2.2 for the description of how to estimate REDD+ activities using IPCC methods, particularly section 2.2.2 on forest degradation.

To facilitate the use of the IPCC GL-AFOLU and GPG reports together with the sourcebook, definitions used in the sourcebook are 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 and sinks of removals of greenhouse gases. For the purposes of this sourcebook, the following categories are considered under the AFOLU sector:

- Forest Land converted to Cropland, Forest Land converted to Grassland, Forest Land converted to Wetlands, Forest Land converted to Settlements, and Forest Land converted to Other Land, are commonly equated with "deforestation".
- Non-forest land converted to forest land would generally be referred to as forestation and is reflected in new forest area being created.

The IPCC Guidelines refer to two basic inputs with which to calculate greenhouse gas inventories: activity data and emissions or removals factors. "Activity data" refers to the extent of a category, and in the case of deforestation, forestation and forest degradation/ enhancements 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 data. "Emission factors" refer to emissions/removals of greenhouse gases per unit area, 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 carbon-stock-change factors for deforestation and forest degradation.

1.2.3.1 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 1.2.2): 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 (e.g. deforestation minus forestation) 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. It may be that for some REDD+ purposes, land use changes will be required to be identifiable and traceable in the future, i.e. it is likely that Approach 3, or Approach 2 with additional information on land use dynamic, can be useful for land tracking[15] and therefore for REDD+ implementation.

Table 1.2.2. 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,

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[15] To achieve accuracy, units of land where use or management practices changed over time can be identified and tracked to ensure the most appropriate emissions factor is applied for estimating GHG net emissions.

not spatially explicit
3. spatially explicit tracking of land-use conversions over time, either by sampling or wall-to-wall

1.2.3.2 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 1.2.3) and which one is selected is in principle 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 forest inventory-type data of carbon stocks in different pools and assessment of any change in pools through repeated measurements which may also be supported by modelling. 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 1.2.3. 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. some combination of detailed national forest inventory, repeated measurements of key stocks through time and modelling

Chapters 2.1 and 2.2 of this sourcebook provide guidance on how to obtain the activity data, or gross and net change in forest area, with low uncertainty. Chapter 2.3 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.

IPCC Tier 1 provides a simplified representation for estimating changes in carbon stocks based on default values. A more complete, representation, with country specific values replacing defaults, is applied at tier 2. At tier 3 countries are free to produce their own country-specific methods, including models, that are capable of providing more complete and accurate estimates (see table 1.2.4).

Table 1.2.4. Mandatory pools to be estimated according to IPCC Guidelines.

TIER 1

		FL		Conversion from forest to other land uses
		FLrFL	LcFL	
LB	*AB*	🟥	🟥	🟥
	BB	🟥	🟥	🟥
DOM	*DW*		🟥	🟥
	L		🟥	🟥
SOM	*SOM*		🟥	🟥

TIERS 2 and 3

		FL		Conversion from forest to other land uses
		FLrFL	LcFL	
LB	*AB*	🟥	🟥	🟥
	BB	🟥	🟥	🟥
DOM	*DW*	🟥	🟥	🟥
	L	🟥	🟥	🟥
SOM	*SOM*	🟥	🟥	🟥

Red shows pools whose carbon stock changes have to be estimated and white, carbon pools assumed, by default, to be in equilibrium.

HWP = Harvested Wood Products (may also be reported applying instantaneous oxidation), LB = Living Biomass pool (AB = aboveground biomass, BB = belowground biomass), DOM = Dead Organic Matter pool (DW = dead wood, L = litter), SOM = Soil Organic Matter pool.

FL = Forest Land, FLrFL = Forest Land remaining Forest Land, LcFL Land converted to Forest Land.

For Forest remaining forest, in practice, under tier 1 the biomass pool accounts for gain (due to vegetation growth) and losses (assumed immediate oxidation of carbon stocks transferred to any other pool). Dead organic matter pools are assumed to be at equilibrium, apart from forests on drained organic soils, which are assumed to lose carbon by oxidation.

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 section 3.1.5). As the reported estimates of reduced emissions may be the basis of an accounting procedure, with the eventual assignment of economic incentives, Tier 3 should be the level to which countries should aspire. 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. This balance could 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 emissions reduction is likely to be underestimated (see also section 1.2.4). Thus, when accuracy of the estimates cannot be achieved, estimates of emissions reductions could be conservative, i.e. likely to be underestimated.

1.2.4 Reference levels and benchmark forest area map

Estimating performance in implementing REDD+ activities requires assessing reference levels against which future emissions and removals can be compared. Conceptually the reference level represents business-as-usual emissions or removals associated with REDD+ activities at national or (as an interim step) at a sub-national level, and is based on historical data and national circumstances.

Credible **reference levels** can be established for a REDD+ system using existing scientific and technical tools, and this is a 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**. A national program to reduce net emissions from deforestation and degradation can benefit from an initial forest area map to represent the point from which each future forest area assessment will be made and actual negative 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. The use of a benchmark map will show where monitoring should be done to assess loss in forest cover. The use of a benchmark map 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 also show where forests exist and how these are stratified either for carbon dynamic, e.g. forest types and management types, or for other national needs.

If only gross deforestation is being monitored, the benchmark map can be updated by subtracting the areas where deforestation has occurred. If forestation needs to be monitored, it is needed to show where non-forest land is reverting to forests a monitoring of the full country territory.

1.3 CLARIFYING REDD+ ELEMENTS CAUSING FOREST CARBON STOCK CHANGE

Under the UNFCCC, REDD is understood to include reduced deforestation and degradation, while REDD+ includes these but also forest enhancement, sustainable management of forests and forest conservation. Between them, these five activities cover three different principles as regards climate change mitigation: reduction of emissions; enhancement of the rate of sequestration; maintaining existing forest reservoirs. The grouping as it currently stands reflects the history of the policy debate in which first ´avoiding deforestation´ was recognized as an important goal, to which ´avoiding degradation´ was quickly appended. The additional elements making up REDD+ entered the debate more recently. ´D and D´ are sometimes seen as being closely related, and rather different from the other three elements.

Deforestation: is the conversion from forest land to another land use. The *forest* definition is largely decided by each country (within limits). Under the KP in decision 16/CMP.1[16] there is agreement on how forest is defined in terms of tree canopy cover, height and area thresholds. Countries may select a canopy cover threshold of between 10 and 30%, with a height minimum of between 2 and 5 meters (of trees at maturity), and an area criterion with a minimum between 0.05 and 1 hectare. Whether an area of forest drops below the threshold and a new use occurs, then the land is considered to have been *deforested*. In other words, it has undergone change from forest to non-forest (i.e., to agriculture, pasture, urban development, etc.). Loss of forest related to a change in land use that prevents natural forest re-growth usually results in considerable carbon emissions, and preventing deforestation from happening is therefore a primary objective of REDD+ (see sections 2.1 and 2.3 for monitoring techniques).

Degradation: while there are more than 50 definitions of forest degradation (Simula, 2009, Herold et al. 2011); degradation is often taken to refer to sustained loss of carbon stock within forests that remain forests. More specifically, degradation represents a human-induced negative impact on carbon stocks, with measured forest variables (i.e. canopy cover) remaining above the threshold for the definition of forest. Moreover, to be

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[16] http://unfccc.int/resource/docs/2005/cmp1/eng/08a03.pdf

distinguished from (sustainable) forestry activities, the decrease should be considered of some level of persistence. A group convened by IPCC to resolve the definition of degradation (Penman et al., 2003) did not produce a clear definition because losses of biomass in forest may be temporary or cyclical and therefore essentially sustainable, even if on average the carbon stock remains below that of intact forest. Realizing that in addition to the variables used to define deforestation, a time element was also required, the IPCC expert group also recognized that selecting such a threshold is difficult. This is in part because forestry cycles are usually much longer than commitment or accounting periods under climate change agreements. A special UNFCCC workshop on degradation convened in 2008[17] and discussed various methodological issues relating to degradation, but although some interesting suggestions emerged, a clear definition was not concluded and not agreed (UNFCCC, 2008).

Measuring forest degradation and related forest carbon stock changes is more complicated and less efficient than measuring deforestation since the former is based on changes in the structure of the forest that do not imply a change in land use and therefore is not easily detectable through remote sensing. There is no one agreed method to monitor forest degradation. The choice of different approaches depends on a number of factors including the type of degradation, available data, capacities and resources, and the possibilities and limitations of various monitoring approaches (see Sections 2.2 and 2.3).

IPCC LULUCF guidance for estimation and reporting on "forest land that remains forest land" has a logical link to degradation, since this reporting requires estimation of net carbon change in forests remaining forests (gains in carbon stocks minus losses). Net increase of carbon stocks – *forest enhancement* – may be achieved through a number of human activities such as enrichment planting, but also by regulation of off-take to levels that are lower than the rate of increment (this might be thought of as the inverse of *degradation*), or by forest expansion. *Sustainable management of forests* (SMF) generally means bringing the rate of extraction in line with the rate of increment. The linking of degradation to deforestation rather than to these new elements in REDD+ is partly the result of the (in many cases false) idea that degradation just a step on the path to full deforestation. In reality, deforestation is usually the result of a decision by a particular actor to change land use, while degradation is usually a gradual process, resulting from decisions of many actors over time as regards to extraction of forest products. The link sometimes made between deforestation and degradation is partly because degradation, like deforestation, is responsible for emissions, while the new elements under REDD+ have to do with sinks.

Sustainable Management of Forests (SMF) is related to sustainable forest management, a term usually used in the context of commercial timber operations, better described as sustained yield management. But there are other ways in which forest can be managed sustainably, for example through community forest management (CFM).

From a practical point of view it makes sense to consider degradation as a form of (unsustainable) forest management, which can best be tackled through improved management and strengthened institutional arrangements, rather than as a minor form of deforestation. This is because degradation is a manifestation of the ways that people use forest that remains forest, rather than a complete change of land use. Also, from a monitoring perspective, degradation, like forest stocks enhancement and SFM, requires sequential stock change measurements, which is rather different from what is needed for monitoring deforestation. For assessing reductions in degradation, as in assessing forest stocks enhancement and SFM, what matters is the *change in the rate at which carbon stock had been changing* in the reference level.

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[17] http://unfccc.int/methods_science/redd/items/4579.php

The remaining item under REDD+ is *forest conservation*. The following considerations are important in understanding the role of forest conservation under REDD+:

- ❑ it is an effort to decrease the threat that forests may become a source of carbon emissions in the future and to ensure permanence by establishing long-term commitments to preserve forest;
- ❑ it implies that disturbances due to human activities in such areas are minimal, and in sum, will result in a net zero carbon balance (or natural increase) in the near and long-term;
- ❑ it may refer to any forest type within a country, but in particular to those with high ecological value and considered at risk of disturbance or carbon stock loss through human activities; and
- ❑ it could result in the continued supply not only of carbon but also of other ecosystem services, provided the ecosystem remains intact.

Following IPCC good practice guidance, forest conservation can be understood as a specific type of forest management and is already covered under "forest land remaining forest land". The monitoring objective is to verify that in conserving forests (i.e. through a policy), the carbon-stock changes deviate from those fixed in the reference level[18]. So that incentive payments for forest conservation under REDD+ would work as deforestation, degradation, forest enhancement and SFM that will all be based on credits issued proportionally to changes in the rate of change of carbon stock.

1.4 EMERGING ISSUES FOR REDD+ IMPLEMENTATION

As REDD+ moves to implementation, participating countries may need to address a number of issues in addition to developing the capacity to monitor and report on carbon emissions. These issues include:

- ❑ to identify agricultural and other land use activities in developing countries, in particular those that are linked to the drivers of deforestation and forest degradation in order to devise effective policies to reduce emissions;
- ❑ the consideration of safeguards to ensure the consistency of national programs, transparency, protection of biodiversity and knowledge and rights of stakeholders; and monitoring of displacement of emissions and permanence at a national scale, and
- ❑ the consideration and integration of national and sub-national monitoring to ensure the detection and tracking of REDD+ activities and associated carbon stocks changes and non-CO_2 emissions; which often are of local focus.

Remote sensing provides some capability to address these issues, though ground-based information and other data from national and international census is an important component. Section 2.9 highlights technical approaches to address these issues, focusing on the contribution of remote sensing.

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[18] The authors do not believe that under REDD+ there will be five different reference levels, one for each activity. It is believed that there will be a single reference level, which will compensate the impact of all five activities on forest carbon stocks. Because of the presence of conservation, enhancement and degradation (deforestation is at the end an extreme case of degradation), the reference level could consist in a net "reduction of emissions/enhancement of removals" or in a limited increase of emissions. Otherwise, a REL where only emissions associated with deforestation and degradation human activities are included, could be complemented by a RL where all removals from forest land and other emissions associated with the remaining REDD+ activities are included.

1.5 ROADMAP FOR THE SOURCEBOOK

The sourcebook is designed to be a guide to develop reference emissions levels and reference levels and to design a system for monitoring and reporting carbon stocks changes from deforestation, forestation and in forest land at the national scale, based on the general requirements set by the UNFCCC and the specific methodologies for the land use sector provided by the IPCC.

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 and removals of carbon, in a format that is user-friendly. It is intended to complement the GPG-LULUCF and GL-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 remainder of the sourcebook is organized in three main sections as follows:

Chapter 2:	GUIDANCE on METHODS
Chapter 3:	PRACTICAL EXAMPLES
Chapter 4:	COUNTRY CAPACITY BUILDING

1.6 KEY REFERENCES FOR CHAPTER 1

Herold M, Román-Cuesta RM, Mollicone D et al. (2011) Options for monitoring and estimating historical carbon emissions from forest degradation in the context of REDD+. *Carbon Balance and Management* 6:13

IPCC (2003) Good Practice Guidance on Land Use, Land-Use Change and Forestry. Eds Penman J, Gytarsky M, Krug et al. IGES, Japan.

IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories. Eds Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K. IGES, Japan

IPCC (2003) Definitions and Methodological Options to Inventory Emissions from Direct Human induced Degradation of Forests and Devegetation of Other Vegetation Types. Eds: Penman J, Gytarsky M, Krug T et al. IPCC-IGES, Japan

Simula M (2009) Towards defining forest degradation: comparative analysis of existing definitions. FAO FRA Working Paper 154 Rome, Italy: FAO

UNFCCC 2008 Informal meeting of experts on methodological issues related to forest degradation. Chair's summary of key messages. Bonn, October 20-21, http://unfccc.int/methods_science/redd/items/4579.php

UNFCCC (2011) Decisions adopted by COP16 ("The Cancun Agreements") on Policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries, UN-FCCC/CP/2010/7/Add.1 Decision 16/CMP.1

UNFCCC (2012) Decisions adopted by COP17, on Guidance on systems for providing information on how safeguards are addressed and respected and modalities relating

to forest reference emission levels and forest reference levels, UNFCCC/CP/2011/9/Add.2 Decision 12/CP17

2 GUIDANCE ON METHODS

The focus of Chapter 2 is on the descriptions of available and operational methods for data collection and measurements to capture changes in forest areas and carbon stocks. Stratification and sampling strategies for estimating forest area changes and carbon stock changes in the context of REDD+ activities are described. Existing approaches to estimate emissions due to land cover changes are described with their requirements in terms of data, levels of complexity and expected outputs and accuracies.

Chapter 2 is organized as follows:

2.1 Monitoring of changes of forest areas (deforestation and forestation)

2.2 Monitoring of forest area changes within forests

2.3 Estimating carbon stocks and stock changes

2.5 Estimation of carbon emissions and removals

2.6 Estimating GHG emissions from biomass burning

2.7 Estimation of uncertainties

2.8 Methods to address emerging issues

2.9 Guidance on reporting

2.10 Evolving technologies

Chapter 3 presents practical examples on the operational application of methods described in Chapter 2, with recommendations for capacity building.

Sections 2.1 and 2.2 present 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 changes of forest areas (i.e. deforestation and forestation) in section 2.1 and for monitoring of changes within forest land (i.e. forest land remaining forests land, e.g. forest degradation) in section 2.2. It includes general recommendations (e.g. for establishing historical reference scenarios) and detailed recommended steps for monitoring changes of forest areas or in forest areas.

The Section builds from "Approach 3" of the IPCC GL 2006 for representing the activity data, or the change in area of different land categories. Approach 3 extends Approach 2, which involves tracking of land conversions between categories, by using spatially explicit land conversion information. Only Approach 3 allows estimating gross-net changes within a category, e.g. to detect a deforestation followed by afforestation.

Sections 2.3 and 2.4 presents guidance on the estimation of the emission factors—the changes in above ground biomass and organic carbon soil stocks of the forests being deforested and degraded.

The second components involved in assessing emissions from REDD+ related activities is the emission factors—that is, the changes in carbon stocks of the forests undergoing change that are combined with the activity data for estimating the emissions. The focus in this Section will be on estimating emission factors. Guidance is provided on: (i) which of the three IPCC GL AFOLU Tiers to be used (with increasing complexity and costs of monitoring forest carbon stocks) (ii) potential methods for the stratification by Carbon Stock of a country's forests and (iii) actual Estimation of Carbon Stocks of Forests Undergoing Change (steps to implement an inventory). Issues of land stratification to assess carbon stock changes are also addressed. Although little attention is given here to areas undergoing afforestation and reforestation, the guidance provided will be applicable.

Section 2.5 presents guidance on the estimation of carbon emissions and removals from changes in forests areas. This Section builds on previous Sections and deals in particular on the linkage between the remote sensing imagery estimates of changes in areas, estimates of carbon stocks from field / in-situ data and the use of biophysical models of carbon emission and removals.

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, which require country-specific data, and Tier 3 IPCC methods which require expertise in more complex models or detailed national forest inventories. Issues of levels of complexity of the models and propagation of errors will also be addressed.

Section 2.6 (Estimating GHG's emissions from biomass burning) is focused on fires in forest environments and approaches to estimate greenhouse gas emissions due to vegetation fires, using available satellite-based fire monitoring products, biomass estimates and coefficients. It provides information on the IPCC guidelines for estimating fire-related emission and on existing systems for observing and mapping fires and burned areas.

Section 2.7 (Estimation of uncertainties) aims to provide some basic elements for a correct estimation on uncertainties. After a brief explanation of general concepts, some key aspects linked to the quantification of uncertainties are illustrated for both area and carbon stocks. The Section concludes with the methods available for combining uncertainties and with the standard reporting and documentation requirements.

The proper manner of dealing with uncertainty is fundamental in the IPCC and UNFCCC contexts.

Section 2.8 (Methods to address emerging issues) focuses on the remote sensing contributions to emerging issues for REDD+ implementation. These issues include:

- to identify land use, land-use change and forestry activities that are linked to the drivers of deforestation and forest degradation;
- the consideration of safeguards to ensure the consistency of national programs, transparency, protection of biodiversity and rights of stakeholders, and monitoring of displacement of emissions and permanence at a national scale; and
- the consideration and integration of national and sub-national monitoring to ensure the tracking of REDD+ activities.

Section 2.9 (Guidance on reporting) gives an overview of the current reporting requirements under UNFCCC, including the general underlying principles and the typical structure of a GHG inventory. The major challenges that developing countries will likely encounter when implementing the reporting principles are outlined. The reporting concepts already agreed upon in a UNFCCC context are described together with a conservative approach which may help to overcome some of the potential challenges.

Under the UNFCCC, 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 but also on the way this information is compiled and presented.

Section 2.10 (Evolving technologies) describes new technologies and approaches which are being developed for monitoring changes in forest area, forest degradation and carbon stocks. These evolving technologies and data sources are described with consideration of their development status, complementary potential, availability for developing country, resources needed for implementation, future perspectives of utility enhancement. The descriptions are limited to basic background information and general approaches, potentials and limitations.

2.1 MONITORING CHANGES IN FOREST AREA

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2.1.1 Scope of Chapter

Section 2.1 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 describes approaches and data for monitoring changes in forest area (i.e., deforestation and forestation) and includes general recommendations (e.g., for establishing historical dataset) and detailed recommended steps for monitoring changes in forest area.

The section presents the minimum requirements to develop first order national forest area change databases using typical and internationally accepted methods. More advanced and costly approaches such as data collection by drones may lead to more accurate results and would meet the reporting requirements.

Remote sensing techniques can be used to monitor changes in forest area (i.e., from forest to non-forest land – deforestation – and from non-forest land to forest land - forestation). The techniques to monitor changes in forest area (e.g. deforestation) provide high-accuracy 'activity data' (i.e., area estimates) and can contribute to reducing the uncertainty of emission factors through spatial mapping of main forest ecosystems. Estimates of forestation area has greater uncertainty than estimates of deforestation area.

This Section describes remote sensing techniques that can be used to monitor changes in forest area (i.e., deforestation and expansion of forest area).

2.1.2 Monitoring changes in forest area - deforestation and forestation

2.1.2.1 General recommendation for establishing a historical reference scenario

As a minimum requirement, use of Landsat-type remotely sensed data (30 m resolution) for years 1990, 2000, 2005 and 2010 is recommended for monitoring forest cover changes with 1 to 5 ha Minimum Mapping Unit (MMU). Use of data from a year prior or after 1990, 2000, 2005 and 2010 may be necessary due to non-availability and cloud contamination. These data facilitate assessing changes in forest area (i.e., to estimate area deforested and forest regrowth for the period considered) and, if desired, producing a map of national forest area (to estimate 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 may preferred as a simple, robust and cost effective method.

Spatial units of different sizes may be used for the detecting forest and forest change. Remote sensing data analyses become more difficult and more expensive with smaller MMUs, 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: the Brazil's PRODES system for monitoring deforestation in the Brazilian Legal Amazon region (6.25 ha initially[19], now 1 ha for digital processing), India's national forest monitoring (1 ha), the EU-wide CORINE land cover/land use change monitoring (5 ha), the 'GMES Service Element' Forest Monitoring (0.5 ha), the Peruvian Ministry of Environment's deforestation monitoring program (0.1 ha), and Conservation International national case studies (2 ha).

Note section 2.1.3 presents and discusses some existing global scale products that a country could use if the construction of local maps is not feasible and no other current local map is available.

2.1.2.2 Key features

Presently the only free global mid-resolution (30m) remote sensing imagery are from NASA's series of Landsat satellites for around years 1990, 2000, 2005 and 2010 with some quality issues in some parts of the tropics (clouds, seasonality, etc.). All Landsat data from the USGS archive have been available for free since the end of 2008. Brazilian/Chinese remote sensing imagery from the CBERS satellites is also freely available in developing countries.

The decades 2000-2010 or 2005-2015 are considered to be more representative of recent historical changes and potentially more suitable due to the availability of complementary data during a recent time frame[20].

Specifications on minimum requirements for image interpretation are:

- ☐ Geo-location accuracy < 1 pixel, i.e. < 30m,
- ☐ Minimum mapping unit between 1 and 6 ha,
- ☐ A consistency assessment should be carried out.

2.1.2.3 Recommended steps

The following steps are needed for a national assessment that is scientifically credible and that 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

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[19] The PRODES project of Brazilian Space Agency (INPE) has been producing annual rates of gross deforestation since 1988 using a minimum mapping unit of 6.25 ha. PRODES has quantified approximately 414,000 km^2 of deforestation in the Brazilian Legal Amazon from 1988 through the year 2015 (http://www.obt.inpe.br/prodes/prodes_1988_2015n.htm), a total that accounts for approximately 12% of the original forest extent. PRODES is being extended to include reforestation and to cover all Brazilian territory.

[20] See first case of National submission to UNFCCC on a forest reference emission level by Brazil in June 2014 at http://unfccc.int/methods/redd/items/8414.php

        - 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 forest area for acquiring satellite data
    - c. Selection and acquisition of the satellite data
    - d. Analysis of the satellite data (preprocessing and interpretation)
    - e. Assessment of the accuracy

2.1.2.4 Selection and implementation of a monitoring approach - deforestation

2.1.2.4.1 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 1.2.2) 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 produces only land cover information. Local expert or field information is needed to obtain land use information.

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

Many types of land cover exist within national boundaries. REDD+ monitoring needs to cover all forest areas, and the same area needs to be monitored for each reporting period. For REDD+ monitoring related to decreases in forest area, monitoring the entire national extent including non-forest land will not always be necessary or practical. Therefore, a forest mask can be designated initially to identify the area to be monitored for each reporting period (referred to in Section 1.2.2 as the benchmark map).

Ideally, wall-to-wall assessments of the entire national extent would be carried out to estimate forest area according to UNFCCC forest definitions at the beginning and end of the reference and assessment periods (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 estimate the overall forest extent.

Important principles in estimating the overall forest extent are:

- ❑ The area should include all forests within the national boundaries
- ❑ The same overall forest extent should be used for monitoring all forest changes during the assessment period

2.1.2.4.3 Step 3: Selection of satellite imagery and coverage

Fundamental requirements for national monitoring systems are that they estimate changes for all forested area, use consistent methodologies at repeated intervals to obtain accurate results, and use ground-based or very high resolution observations as reference data to verify results. 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 monitoring at national scales.

Many data from optical sensors at a variety of resolutions and costs are available for monitoring deforestation (Table 2.1.1).

Table 2.1.1. Utility of optical sensors at multiple resolutions for monitoring deforestation.

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 - 2012) VIIRS (2012-)	~ 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 data
Medium (10-60 m)	Landsat TM or ETM+, Sentinel-2A/B Terra-ASTER IRS AWiFs or LISS III CBERS HRCCD DMC SPOT HRV ALOS AVNIR-2	0.5 - 5 ha	Landsat & CBERS are free; for others: <$0.001/km² for historical data $0.02/km² to $0.5/km2 for recent data	Primary tool to map deforestation and estimate area change
Fine (<5 m)	RapidEye IKONOS QuickBird Pleiades	< 0.1 ha	High to very high $2 -30 /km²	Use as reference data for validating results from coarser resolution analysis, and for training algorithms
Very Fine (<1 m)	GeoEye WorldView Drones Aerial photos	< 0.01 ha	High to very high $2 -30 /km²	Use as reference data for validating results from coarser resolution analysis, and for training algorithms

Availability of medium resolution data

The American 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 7 covers the same ground track repeatedly every 16 days. The Landsat Data Continuity Mission (Landsat 8) was launched on 11 February 2013 to continue the series.

Almost complete global coverage from these Landsat satellites for early the 1990s, early 2000s, around year 2005 and around year 2010 are available for free download through web-portals at USGS[21] and from the University of Maryland's Global Land Cover Facility[22]: the Global Land Survey (GLS) Datasets. These data serve a key role in estimating historical deforestation rates, although in some parts of the humid tropics (e.g. Central Africa) persistent cloudiness is a major limitation to use of these data. On April 2003, the Landsat 7 ETM+ scan line corrector failed resulting in data gaps outside of the central portion of each image, compromising data quality for land cover monitoring. Given this failure, NASA, in collaboration with USGS, acquired and composed appropriate imagery to generate the GLS 2005 and GLS 2010 datasets by combining Landsat 5 and Landsat 7 images. The GLS-2000, GLS-2005, and GLS-2010 datasets provide almost complete coverage of the land area of the Earth, with less than 1% not covered. These data have been processed to a new orthorectifed standard using data from NASA's Shuttle Radar Topography Mission.

The USGS has established no-charge Web access to the full Landsat USGS archive[23]. The full Landsat 8 OLI (since June 2013) and Landsat 7 ETM+ (since 1999) archives, and all USGS archived Landsat 5 TM data (since 1984), Landsat 4 TM (1982-1985) and Landsat 1-5 MSS (1972-1994) can now be ordered at no charge.

Until now, Landsat's low cost and unrestricted license use has made it the workhorse source for mid-resolution (10-50 m) data analysis. Alternative sources of data include ASTER, SPOT, IRS, CBERS, DMC or AVNIR-2 data (Table 2.1.2).

Selection of the satellite images for use in any assessment must consider seasonality and climate. For forest types with seasonal features (i.e., a distinct dry season where trees may drop their leaves) more than one satellite image should be used. Inter-annual variability must be considered based on climatic variability.

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[21] http://glovis.usgs.gov/

[22] http://landcover.org/

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

Table 2.1.2. Present availability of optical mid-resolution (10-60 m) sensors.

Nation	**Satellite & sensor**	**Resolution & coverage**	**Cost for data acquisition (archive[24])**	**Feature**
Europe	Sentinel-2A	10, 20, 60 m	Free and open access	Data will be systematically acquired from June 2016
USA	Landsat-8 OLI	30 m 180×180 km²	All data archived at USGS are free	Data have been systematically acquired since June 2013
USA/Japan	Terra ASTER	15 m 60×60 km²	60 US$/scene 0.02 US$/km²	Data are acquired on request and are 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 and potentially for other developing countries	Experimental; Brazil uses on-demand images to bolster their coverage.
Algeria/ China/ Nigeria/ Turkey/ UK	DMC	22 - 32 m 160×660 km²	3000 €/scene 0.03 €/km²	Commercial; Brazil uses alongside Landsat data
France	SPOT-5 HRVIR	10-20 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. Data from other, newer, types of sensors such as radar (ERS1/2 SAR, JERS-1, ENVISAT-ASAR and ALOS PALSAR 1/2) and lidar are potentially useful and appropriate. Radar, in particular, 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 forest monitoring over large areas. Over the next years, the utility of radar may be enhanced depending on data acquisition, access and scientific developments.

In summary, Landsat-type data around years 1990, 2000, 2005 and 2010 will be most suitable to assess historical rates and patterns of deforestation. The availability of free and open Landsat data has increased for more recent years, thus making detailed assessments for coverages of less than five years may now be possible in many parts of the world.

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 obtaining cloud-free

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[24] 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.

observations. The greater temporal resolution increases the likelihood of cloud-free images and can augment data sources where persistent cloud cover is problematic. Coarse resolution data also have cost advantages, offer complete spatial coverage, and reduce the amount of data that must 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 finer 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 for assessing change over large nations. In cases where clearings are large and/or change is rapid, visual interpretation or automated analysis can be used to identify where change in forest area has occurred. Automated methods such as mixture modelling and regression trees (Box 2.1.1) can also identify changes in tree cover at the sub-pixel level. Validation of analyses with medium and fine resolution reference data for selected locations can be used to assess accuracy and compensate for classification error. The use of coarse resolution data to identify deforestation hotspots is particularly useful for assisting in the design of an efficient sampling strategy (see following section).

Box 2.1.1. 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 2.1.5 for more details)

Utility of fine or very fine resolution data

Fine resolution (< 5m) data, such as those collected from commercial sensors (e.g., IKONOS, QuickBird, RapidEye) and data acquired by aircraft or drones, can be prohibitively expensive for coverage of large areas. However, these data can be used to calibrate algorithms for analyzing medium and high resolution data and as reference data for verifying results, i.e., they can be used as a tool for "ground-truthing" the interpretation of satellite imagery and/or for assessing the accuracy.

2.1.2.4.4 Step 4: Decisions for sampling versus wall-to-wall coverage

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

The following main criteria can be used to decide whether to use sampling or wall-to-wall coverage:

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 cost-efficient, particularly for large countries

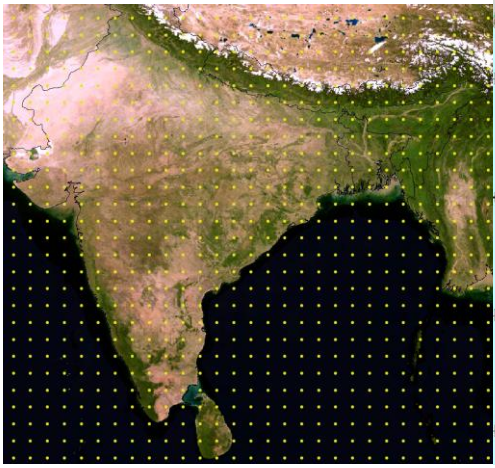
- Recommended sampling approaches are systematic and stratified sampling (see box 2.1.2).
- A sampling approach for one reporting period could be extended to wall-to-wall coverage for a subsequent period.

Box 2.1.2. Systematic and stratified sampling

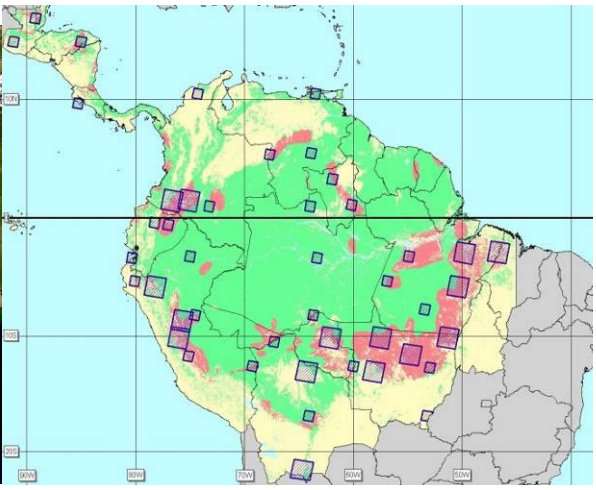
Systematic sampling selects units for the sample that are distributed at regular spatial intervals, e.g., at the intersections of a 10-km x 10-km grid.

Sampling efficiency can be improved through spatial stratification (‘stratified sampling’) using a wide variety of proxy variables including deforestation hot spots, climatic and topographic information, combinations of geo-referenced information such as distance to roads or settlements, previous deforestation, fire locations, and coarse resolution remotely sensed data.

Example of systematic sampling



Example of stratified sampling



A stratified sampling approach for forest area change estimation has been 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 estimate biome-wide area of forest clearing. Change estimates can be estimated at country level by adapting the sample to the country territory.

A few very large countries including 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 for further details). Brazil has estimated deforestation rates in Brazilian Amazonia since the end of the 1980s. These methods could be easily adapted for use in smaller countries. Global wall-to-wall maps of tree cover and tree cover losses/gains over the period 2000-2012 were published at the end of 2013[25] , with reported accuracies greater than 80% for tropical and sub-tropical domains, and are now available from year 2000 until very recent years through the Global Forest Watch web site[26].

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[25] Hansen MC et al (2013) High-resolution global maps of 21st-century forest cover change. *Science* 342, 850-853

[26] http://www.globalforestwatch.org/

Although wall-to-wall coverage is ideal, it may not be either financially or logistically practical for large areas due to the resources necessary to produce sufficiently accurate estimates.

2.1.2.4.5 Step 5: Process and analyze the satellite data

Step 5.1: Preprocessing

Satellite imagery usually requires three main pre-processing steps: (1) geometric corrections to ensure that images in a time series overlay properly, (2) cloud removal, and (3) radiometric corrections to facilitate change interpretation by ensuring that images have the same spectral values for the same objects.

- ☐ Geometric corrections
    - Small geolocation error in change datasets must be ensured: average geolocation error (relative between two images) should be less than 1 pixel width
    - Existing Landsat GLS data usually provide sufficient geometric accuracy and can be used as a baseline; for limited areas Landsat GLS has geolocation problems
    - Using additional data such as non-GLS Landsat, SPOT, etc. requires 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 must be removed for automated approaches
- ☐ Radiometric corrections
    - Effort needed for radiometric corrections depends on the change assessment approach
    - For simple scene-by-scene analysis such as 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 multi-temporal datasets. This is usually done by identifying a water body or dark object and calibrating the other images to the first.
    - Reduction of haze may be a useful complementary option for digital approaches. Image contamination by haze is relatively frequent in tropical regions. Therefore, when no alternative imagery is available, haze correction is recommended before image analysis. Partially haze contaminated images can be corrected through a tasseled cap transformation[27].
    - Topographic normalization is recommended for mountainous environments from a digital terrain model (DTM). For medium resolution data the SRTM

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[27] Lavreau J (1991) De-hazing Landsat Thematic Mapper images, *Photogrammetric Engineering & Remote Sensing,* 57:1297–1302.

(shuttle radar topography mission) DTM can be used with automated approaches[28]

Step 5.2: Analysis methods

Many methods can be used to interpret images (Table 2.1.3). 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.

Prediction of areas of forestation area is generally more difficult than prediction of areas of deforestation. Forestation occurs gradually over multiple years whereas deforestation occurs more rapidly and is therefore more easily predicted from time series of remotely sensed data. Finer resolution data, additional field work, and accuracy assessment may be required if forestation, as well as deforestation, must be monitored.

Visual scene-to-scene interpretation of forest area 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 results by an analyst familiar with the region should be carried out to ensure appropriate interpretation.

A preliminary visual screening of image pairs can serve to predict 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 estimation of the area of change).

Changes (for each image pair) can then be predicted by comparing the two multi-date final forest maps. The timing of image pairs must 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 entities

Visual delineation is a viable method, particularly if image analysis tools and experiences are limited. Visual delineation of land entities on printouts (used in former times) is not recommended. On-screen delineation is preferred because it produces direct digital results. When land entities are delineated visually, they should also be labeled visually.

Table 2.1.3. Main analytical methods for use with medium 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

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[28] 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.

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 for image analysis. The delineation provided by this approach is not only more rapid and automatic but also finer than could be achieved using a manual approach. It is repeatable and, therefore, more objective than 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 estimate change.

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

I. Multi-date image segmentation is applied on image pairs: groups of adjacent pixels that exhibit similar area change trajectories between the two dates are delineated into objects.

II. Training areas are selected for all land classes for each of the two dates (in the case of more than one image pair and if all images are radiometrically corrected, this step can be prepared initially by selecting a set of representative spectral signatures for each class – as average from different training areas)

III. Objects from every extract (i.e., every date) are classified separately by supervised clustering procedures, leading to automated forest maps, one for each of the first and second dates

IV. Visual interpretation is conducted interdependently on the image pairs to verify/adjust the label of the classes and edit possible automated 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 into clusters applies in the case of automated delineation of segments.

After segmentation, application of two supervised object classifications separately on the two multi-date images is recommended instead of applying a single supervised object classification on the image pair. The reason is that two separate land classifications are much easier to produce in a supervised step than a direct classification of change trajectories.

The supervised 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).

Although unsupervised clustering (followed by visual labeling) is also possible, for large areas (i.e., for more than a few satellite scenes) application of supervised object classification (with a training phase beforehand and a labeling correction/validation phase afterwards) is recommended. An unsupervised direct classification of change trajectories for the two multi-date images together implies a second step of visual labeling of the classification result into the different combination of change classes which is a time-consuming task. Multi-date segmentation followed by supervised classification of individual dates is considered more efficient in the case of a large number of images. Other methodological options (see Table 2.1.3) can be used depending on the specific conditions or expertise within a country.

General recommendations for image object interpretation methods

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

- ❑ Interpretation should focus on change in land use with interdependent visual assessment of two multi-temporal images together. Contrarily to digital classification techniques, visual interpretation is easier with multi-temporal imagery.
- ❑ 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 must be considered during the interpretation. In the case of seasonal forests, images from the same time of year should be used. Preferably, multiple images from different seasons would be used to ensure that changes in forest cover from inter-annual variability in climate are not confused with deforestation.

2.1.2.4.6 Web-based approaches

The current trends in technology adoption and internet access suggest that cloud-based remote sensing processing can offer a complementary solution for the increasingly amount of remote sensing data.

As an example, Google Earth Engine has been developed as a new technology platform that enables automated remote sensing and ground-sampled data processing and forest mapping. For more details see section 2.10.9 on web-based approaches to support forest monitoring.

2.1.2.4.7 Step 6: Accuracy assessment

An independent accuracy assessment is an essential component of a crediting system. Reporting accuracy and verification of results are essential components of a monitoring system. Accuracy could be estimated following recommendations of section 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 should be used to estimate accuracy.

A detailed description of methods to be used for uncertainty assessment for purposes of using maps to assist in the estimation of land cover area or land cover change area is provided in section 2.6 ("Estimating uncertainties in area estimates").

2.1.2.5 Monitoring of increases in forest area - forestation

Increases in forest area can occur for a variety of reasons, including recovery from fire or storms, natural forest regeneration following crop abandonment, fallow periods in shifting cultivation systems, direct afforestation efforts, and growth of tree plantations. Identifying increases in forest area from remotely sensed data is generally more difficult than identifying decreases from deforestation. Increases in forest area occur relatively slowly, so that increases can only be identified after several years. Even longer periods are needed to identify fallow cycles from shifting cultivation and harvesting cycles for timber plantations. Care should be taken to use images separated by sufficiently long periods of time to avoid erroneous conclusions about increases in forest areas. Time series of images should be used to distinguish seasonal behavior (in particular for deciduous forests which can appear as bare ground during the dry season) from regrowth of secondary forests (e.g. from reforestation/afforestation or crop abandonment). The free availability of data from Landsat and other sensors make it feasible to analyze multiple images in a time series (ideally two images: one image during dry season and another during the wet season).

There are no standard methods for identifying increases in forest cover from remote sensing. The same methods for identifying loss of forest cover can be applied to identify increases, with the precaution that longer time series are required. These methods include visual interpretation, supervised and unsupervised pixel-based classification, and object-based segmentation (see Table 2.1.3).

The Brazilian monitoring system presently carried out by INPE does not identify yet increases in forest area (see section 3.2.2). The biennial wall-to-wall mapping of forest cover by the Indian government identifies classes based on tree cover densities (very dense, moderately dense, and open forest) and can identify areas where the forest density has changed between time periods. Repeated measurements of permanent plots for forest inventories, if available also for initially non forested plots, can provide information about increases in forest area at the sample plot locations.

Plantations are an increasingly important land use in the tropics. Multispectral optical remote sensing data often confuse forests and plantations, particularly with coarse-resolution data (i.e. > 100 m resolution). Developing technologies, including hyperspectral and LIDAR, have the potential to distinguish plantations from forests based on characteristic spectral responses of plantations species (hyperspectral) and vegetation structure (LIDAR). Textural measures, in particular for fine resolution imagery (< 10m) may distinguish plantations due to the regular spacing of planted trees when using automated methods. With data from a long time-series, plantations can be identified through cycles of clearing and/or harvesting, and planting.

2.1.3 Use of Global Products

Construction of remote sensing-based land cover maps typically entails acquisition of the Earth observation data, training data to guide classification or prediction, and reference data for assessing accuracy. In addition to data acquisition, the effort includes the actual classification and accuracy assessment components. These tasks require local expertise and can be costly, laborious, and time-consuming. If construction of a national map is not feasible and no other current national maps are available, then a third alternative is to use one of the existing continental or global forest cover and/or forest cover change maps, preferably in combination with reference local data to be used to calibrate the continental or global maps to the national conditions. Current possibilities include the 30-m x 30-m, Landsat-based, Global Forest Change (GFC) map products[29]; the 30-m x 30-m, GlobeLand30 dataset based on more than 20,000 Landsat and Chinese HJ-1 satellite images[30]; and the global forest/non-forest map based on data from the Advance Land Observation Satellite, Phased Array type L-band Synthetic Aperture Radar[31]. The choice of a particular continental or global map depends on multiple factors including the degree to which the map and local information match with respect to factors such as dates, resolution, and definitions.

The comparability between global dataset attributes and the national forest definition must be carefully considered, particularly the minimum forest cover and minimum area thresholds in the national definition. For example, because the GFC data are in the form of estimates of percent tree canopy cover for all 30-m x 30-m pixels, a percent tree canopy cover threshold must be selected that distinguishes between forest and non-forest. Although selection of a threshold that matches the threshold in the national definition would be tempting, multiple recent studies indicate that percent tree canopy cover thresholds closer to 50% produce results that better match local field-based estimates[32]. In addition, if the resolution of the dataset does not match the minimum area threshold of the national definition, then pixels in the dataset predicted to have forest cover may have to be aggregated to assess whether the aggregations satisfy the minimum area threshold of the national definition. If contiguous aggregations of forest pixels have less area than the minimum area threshold, then those aggregations may have to be relabeled as non-forest.

The important conclusion is that although global datasets have some potential for national uses, calibration of the global data to local conditions is necessary to ensure the

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[29] Hansen MC *et a*l (2013) High-resolution global maps of 21st-century forest cover change. Science 342, 850-853

[30] Jun C, Ban Y, Li S (2014) China: open access to Earth land-cover map. Nature, 514: 434.

[31] Shimada M et al (2014) New global forest/non-forest maps from ALOS PALSAR data (2007–2010). *Remote Sens. Environ.* 155: 13-31.

[32] McRoberts RE et al (2016) Methods for evaluating the utilities of local and global maps for increasing the precision of estimates of subtropical forest area. Canadian Journal of Forest Research 46, 924-932.

relevance and accuracy of results[33]. As with all other spatial products, reference data of greater quality than the GFC data should be used to produce estimates with standard errors for parameters of the population that the GFC data represents[34]. More specifically the use of a sample-based approach using greater quality reference data combined with the wall to wall GFC dataset allow more accurate estimates of tropical forest area losses[35] Further discussion on the topic can be found in the Guidance Module #2 of the Global Forest Observations Initiative (http://www.gfoi.org/methods-guidance/).

2.1.4 Key references for Section 2.1

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[33] Sannier C, McRoberts RE, Fichet LV (2016) Suitability of Global Forest Change data to report forest cover estimates at national level in Gabon. *Remote Sens. Environ.* 173, 326-338.

[34] Nasset E et al (2016) Mapping and estimating forest area and aboveground biomass in miombo woodlands in Tanzania using data from airborne laser scanning, TanDEM-X, RapidEye, and global forest maps: a comparison of estimated precision. *Remote Sens. Environ.* 175, 282-300.

[35] Tyukavina A et al (2015) Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012 *Environ. Res. Lett.* 10 074002

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2.2 MONITORING OF CHANGE IN FOREST LAND REMAINING FOREST LAND

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2.2.1 Scope of section

Section 2.2 presents the state of the art for data and approaches to be used for monitoring changes within forest land (i.e. forest land remaining forests land, e.g. degradation). It includes general recommendations and detailed recommended steps for monitoring changes in forest areas.

The remote sensing techniques can be used to monitor area changes within forest land which leads to changes in carbon stocks (e.g. degradation). The techniques to monitor changes within forest land (which leads to changes in carbon stocks) provide lower accuracy ‘activity data’ and gives poor complementary information on emission factors.

This section focuses on monitoring area changes within forest land which leads to reduction in carbon stocks (i.e. degradation). Techniques to monitor changes within forest land which leads to increase of carbon stocks (e.g. through forest management) are not considered in the present version.

2.2.2 Monitoring of changes in forest land remaining forest land

Many activities cause degradation of carbon stocks within forests but not all of them can be monitored well with high certainty using remote sensing data. As discussed above in Section 1.2.2, 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). Higher intensity logging is likely to cause 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 is usually easier to identify and monitor with existing satellite imagery than logging. Degradation from fires is also important for carbon fluxes. The trajectory of spectral responses on satellite imagery over time is useful for tracking burned area.

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 logging: the direct approach that detects gaps and the indirect approach that detects road networks and log decks. A method to monitor burned forest areas is also presented.

Key Definitions

Intact forest - patches of forest that are not damaged or surrounded by small clearings; forests without gaps caused by human activities.

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

Log landings - a more severe type of damage caused when the forest is cleared for the purposes of temporary timber storage and handling; bare soil is often exposed.

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 - forests recovering from previous disturbance, resulting in carbon sequestration.

Burned Forests - a damage in a forest stand caused by fire, i.e. when the forest is burned through direct or indirect human activities. In humid tropical forests, fires usually lead to an immediate and long term reduction of Carbon stocks, when in dry forests fires can have a limited impact on carbon stocks.

2.2.2.1 Direct approach to monitor selective logging and burning in forest land

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, ASTER 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 images 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 2.2.1). In the case of forest fire, the damage is associated with areas of burned forest and the loss of forest carbon due to these fires.

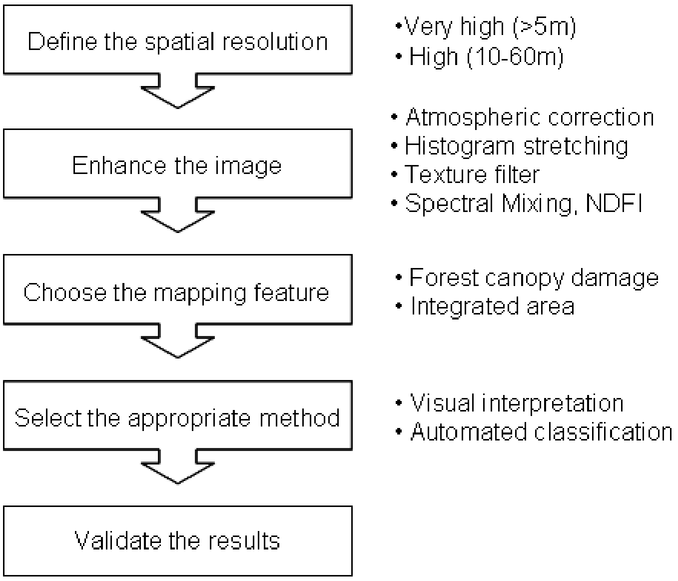
Figure 2.2.1. Very high resolution Ikonos image showing common features in selectively logged forests in the Eastern Brazilian Amazon.

(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 2.5).

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. Moreover, the associated carbon emissions may be higher than for selective logging. The most appropriate approach is to map directly the areas of burned forest during (or at the end of) the burning season.

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



In this chart "Very high (>5m)" should read as "Fine (<5m)" and "High (10-60m)" as "Medium (10-60m)" (refer to Table 2.1.1)

2.2.2.1.1 Step 1: Define the spatial and temporal resolution

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Mapping forest degradation requires an appropriate spatial and temporal resolution of remote sensing imagery. For example, unplanned selective logging usually creates small scale impacts on the forest canopy and establishes barely any infrastructure. Timber trees are felled, cut into manageable pieces and then dragged along narrow skid trails. This procedure causes much less visible impact than managed selective logging which constructs extensive infrastructure (logging roads, skid trails, and landing facilities). Medium resolution optical data, e.g. Landsat (with a spatial resolution of 30 m), is very valuable for historical and present analyses of forest degradation caused by fire and planned logging activities. Due to the minor visible damage of unplanned selective logging on the forest canopy, high resolution remote sensing imagery is required to detect the full extent of forest degradation. The comparison of Landsat (30 m spatial resolution) and RapidEye (6.5 m spatial resolution) imagery within an unplanned selective logged tropical peat swamp forest in Central Kalimantan on Borneo demonstrates that medium resolution satellite data is not capable to map the whole extent of small scale logging (Figure 2.2.2.). Figure 2.2.3. compares satellite images with different spatial resolutions acquired during the same period in the Brazilian Amazon.

Figure 2.2.2. True color Landsat (left) and RapidEye (right) scenes acquired on 22 May 2009 within an unplanned selectively logged peat swamp forest in Central Kalimantan on Borneo.

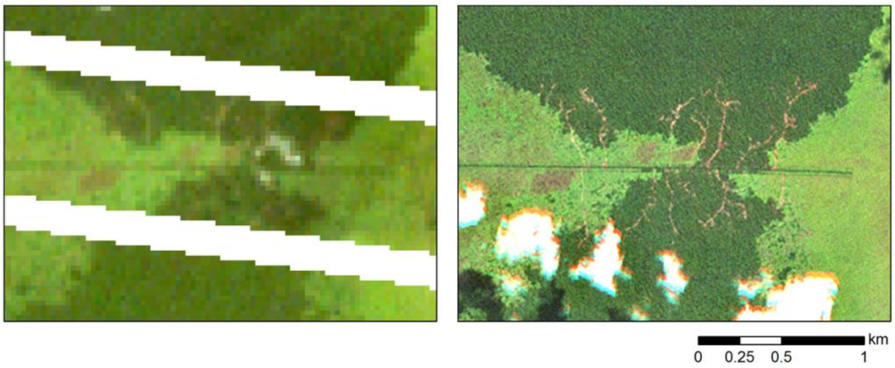
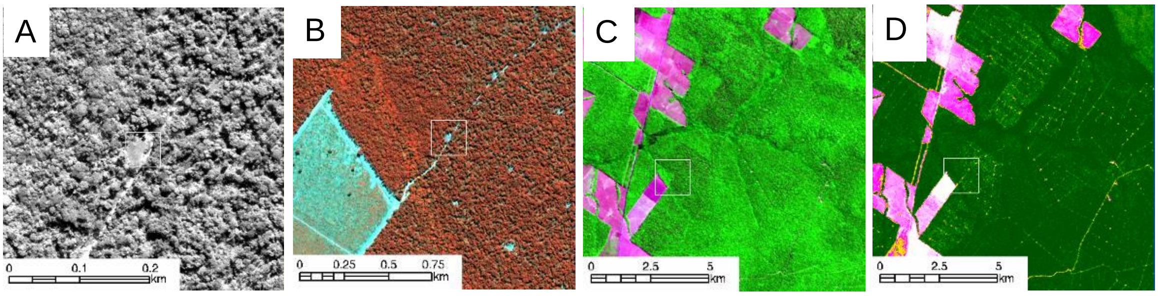


Figure 2.2.3. Unplanned logged forest in Sinop, Mato Grosso, Brazilian Amazon in: (A) IKONOS panchromatic image (1 meter pixel); (B) IKONOS multi-spectral and panchromatic fusion (4 meter pixel); (C) Landsat multi-spectral (R5, G4, B3; 30 meter pixel); and (D) Normalized Difference Fraction Index image (sub-pixel within 30 m). These images were acquired in August 2001.



The minor impact on the forest canopy facilitates rapid expansion and enables fast vegetation regrowth (Figure 2.2.4). Hence, not only high spatial resolution but also high temporal resolution remote sensing data is required to monitor the full extent of the degraded forest area.

For instance, RapidEye data with a swath of 77 km and a repeat cycle of one day has demonstrated to address these spatial and temporal aspects (Franke et al., 2012).

Figure 2.2.4. Temporal progress of unplanned selective logging activities in a tropical peat swamp forest in Central Kalimantan (Borneo) is shown with true color RapidEye images. The acquisition date is depicted above the sces.

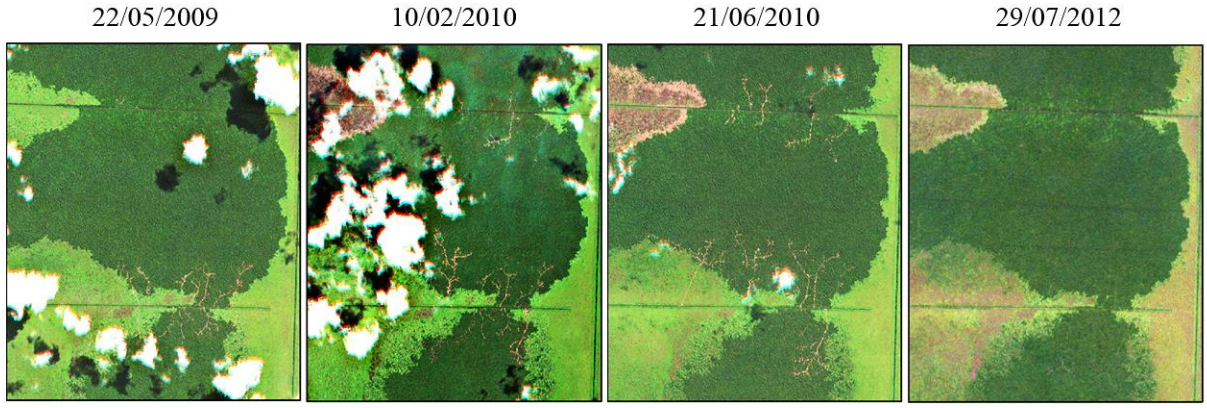
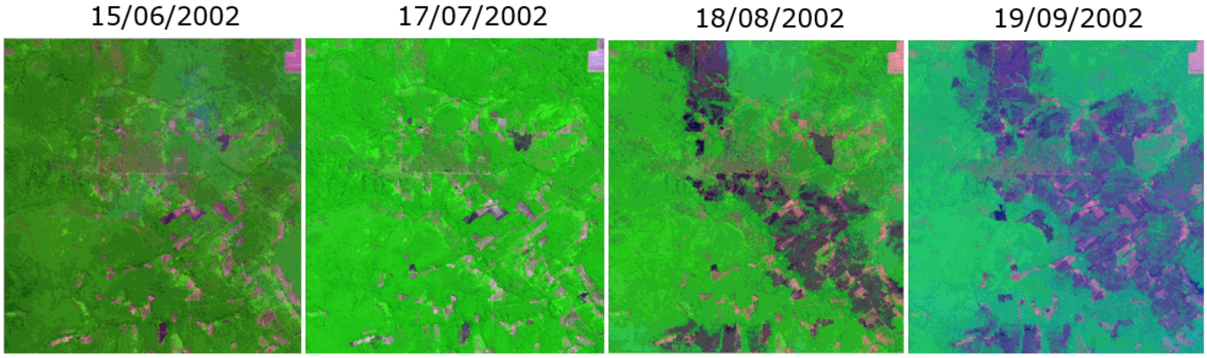
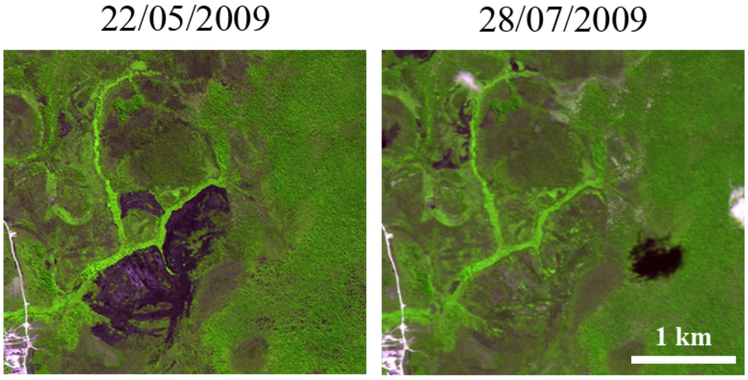

22/05/2009 10/02/2010 21/06/2010 29/07/2012

Figure 2.2.5. Development of forest burning on Landsat imagery in Amazon basin in year 2002.


15/06/2002 17/07/2002 18/08/2002 19/09/2002

A high temporal resolution of satellite imagery is not only important for the monitoring of the full extent of unplanned selective logging but also for mapping burned areas. The rapid vegetation regrowth on areas affected by fire can hinder the detection of burned areas (Figure 2.2.6).

Figure 2.2.6. Rapid vegetation regrowth after fire impact within only two month shown with RapidEye imagery (RGB: bands 452).

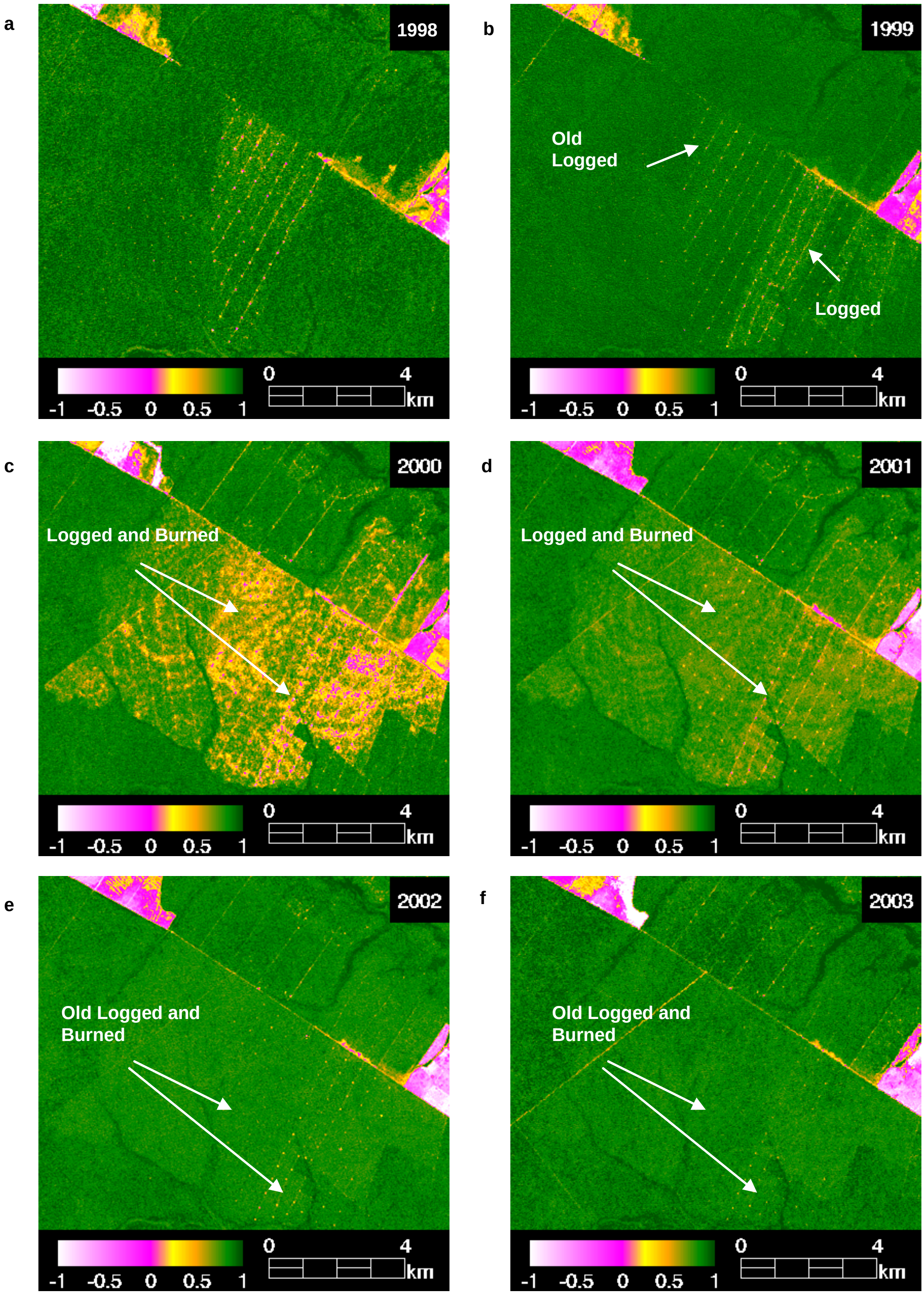


2.2.2.1.2 Step 2: Enhance the image

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 2.2.3C 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; also often called PV or photosynthetic vegetation), 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 2.2.3D shows the same area and image as Figure 2.1.2C 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 2.2.5).

Because the degradation signatures of logging and forest fires change quickly in high resolution imagery (i.e. < one year), annual mapping is required. Figure 2.2.6 illustrates this problem showing logging and forest fires scars changing every year over the period of 1998 to 2003. This has important implications for estimating emissions from degradation because old degraded forests (i.e., with less carbon stocks) can be misclassified as intact forests. Therefore, annual detection and mapping the areas with 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 2.2.6. Forest degradation annual change due to selective logging and logging and burning in Sinop region, Mato Grosso State, Brazil.



2.2.2.1.3 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 2.2.3.A-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 with very high and high spatial resolution imagery.

Data needs

There are several optical sensors that can be used to map forest degradation caused by selective logging and forest fires (Table 2.2.1). 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?

The summary report of the GEO GFOI and GOFC-GOLD joint workshop on forest degradation monitoring (October, 2014) provides a complementary overview of the mapping methods per sensor type, and the R&D efforts that still need to be performed to reach an operational level[36].

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.

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 2.2.1).

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[36] http://www.gfoi.org/documents

Table 2.2.1. 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	Not been tested in very large areas. segmentation rules may vary across the landscape
Textural Filters	Landsat TM5 and ETM+	Brazilian Amazon	Map forest canopy damage associated	Relatively simple to implement	Very difficult to interpret and to validate; confused with forest structure
Combining segmentation, shade fraction images & Visual Interpretation	Landsat TM or ETM+	Local and Brazilian Amazon	Map canopy damage of burned forest	Allows separating burned forest from logged area Semi automatic method	Labor intensive for large areas
CLAS[37]	Landsat TM5 and ETM+, MODIS	Brazilian Amazon, Peruvian Amazon, Indonesia, Global	Map total logging area (canopy damage, clearings and undamaged forest)	Fully automated and standardized to very large areas.	Requires high computation power and pairs of images to detect forest change associated with logging.
CLASlite[38]	Landsat TM, ETM+ ASTER, ALI, SPOT4, SPOT5, MODIS	Regional to national	Rapid mapping of deforestation and degradation	Highly automated, uses a standard computer, requires little expertise	Not available for Apple Macintosh computers
CLAS-BURN[39]	Landsat TM, ETM+	Regional to national	Rapid mapping of sub-canopy fire burn scars	Uniquely sensitive to burn scars, and not logging	Requires testing outside of the Amazon basin

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[37] CLAS: Carnegie Landsat Analysis System

[38] http://claslite.ciw.edu

[39] Carnegie Landsat Analysis System – BURN algorithm (Alencar et al. 2010)

NDFI+CCA[40]	Landsat TM5 and ETM+	Local	Map forest canopy damage associated with logging and burning	enhances forest canopy damaged areas.	It does not separate logging from burning
Spatial mixture analysis	RapidEye	Local	map forest degradation associated with small scale selective logging	High temporal resolution allows motoring of unplanned small scale selective logging despite fast regrowth	not fully automated

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

Box 2.2.1. 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 2.1.3). 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 SMA models produce as output fraction images of each pure material found within the 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 because of exposed wood and dead vegetation, 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:

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

for

$$\sum_{i=1}^{n} F = 1 \tag{2}$$

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 ε_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:

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

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 if 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 2.2.1. Continuation

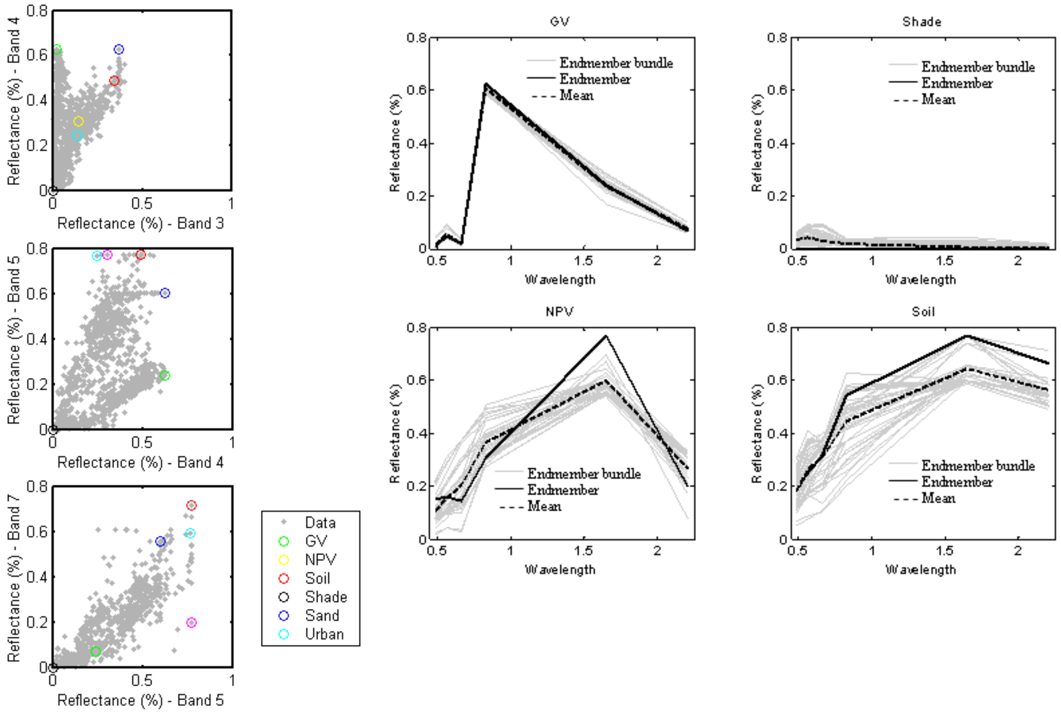

Image scatter-plots of Landsat bands in reflectance space and the spectral curves of GV, Shade, NPV and Soil.

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 wind throws and seasonal changes. Confusion due to seasonality can be reduced by using more frequent satellite observations. 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.

Box 2.2.2. 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:

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

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

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

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. 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.

Progress in developments of national monitoring systems

All the techniques discussed in this section (Direct approach to monitor selective logging) were developed and validated in the Brazilian Amazon. Recent efforts to export these methodologies to other areas are underway. For example, SMA and NDFI 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. The summary report of the GEO GFOI and GOFC-GOLD joint workshop on forest degradation monitoring (October, 2014) provides a complementary overview of the mapping methods per sensor type, and the R&D efforts that still need to be performed to reach an operational level[41].

2.2.2.2 Indirect approach to monitor forest degradation

Often a direct remote sensing approach to assess forest degradation cannot 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. species compositions) or ecosystems than can be delineated

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[41] http://www.gfoi.org/documents

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 largely adapts the concepts and criteria already developed to assess the world's intact forest landscape in the framework of the IPCC Guidance and Guidelines for reporting GHG emissions and removals 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 a 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 is 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.

2.2.3. Method for delineation of intact forest landscapes

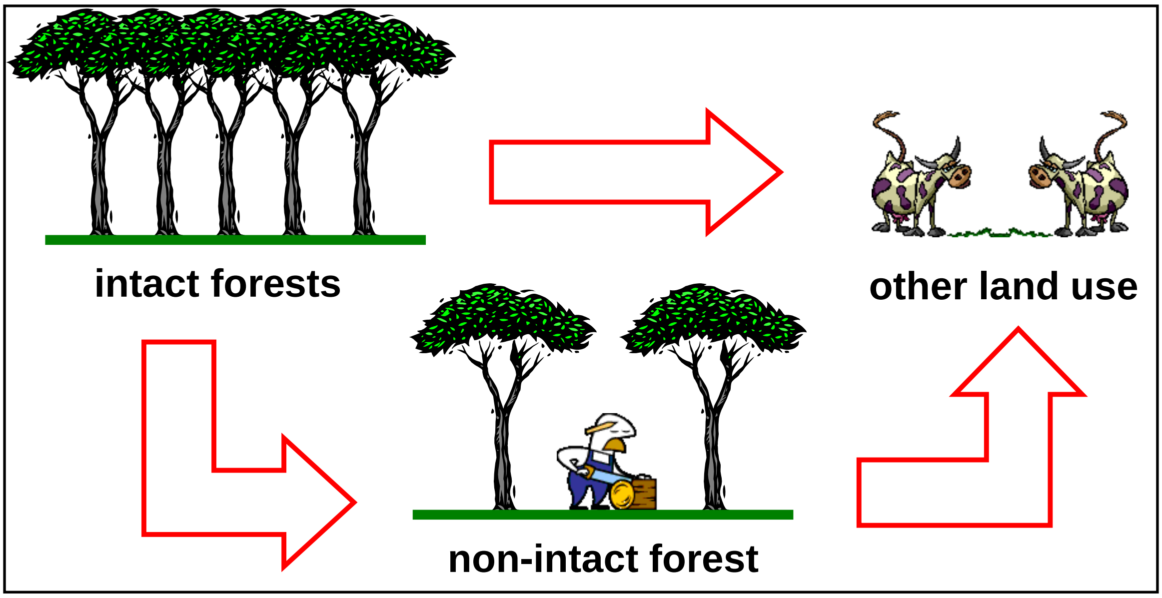
A two-step procedure could be used to exclude non-intact areas and delineate the remaining intact forest:

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 with 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 2.2.7, 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 consists 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 developed in the IPCC LULUCF Guidance and AFOLU Guidelines for the sections "Forest land remaining Forest land".

Figure 2.2.7. 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 2.2.8).

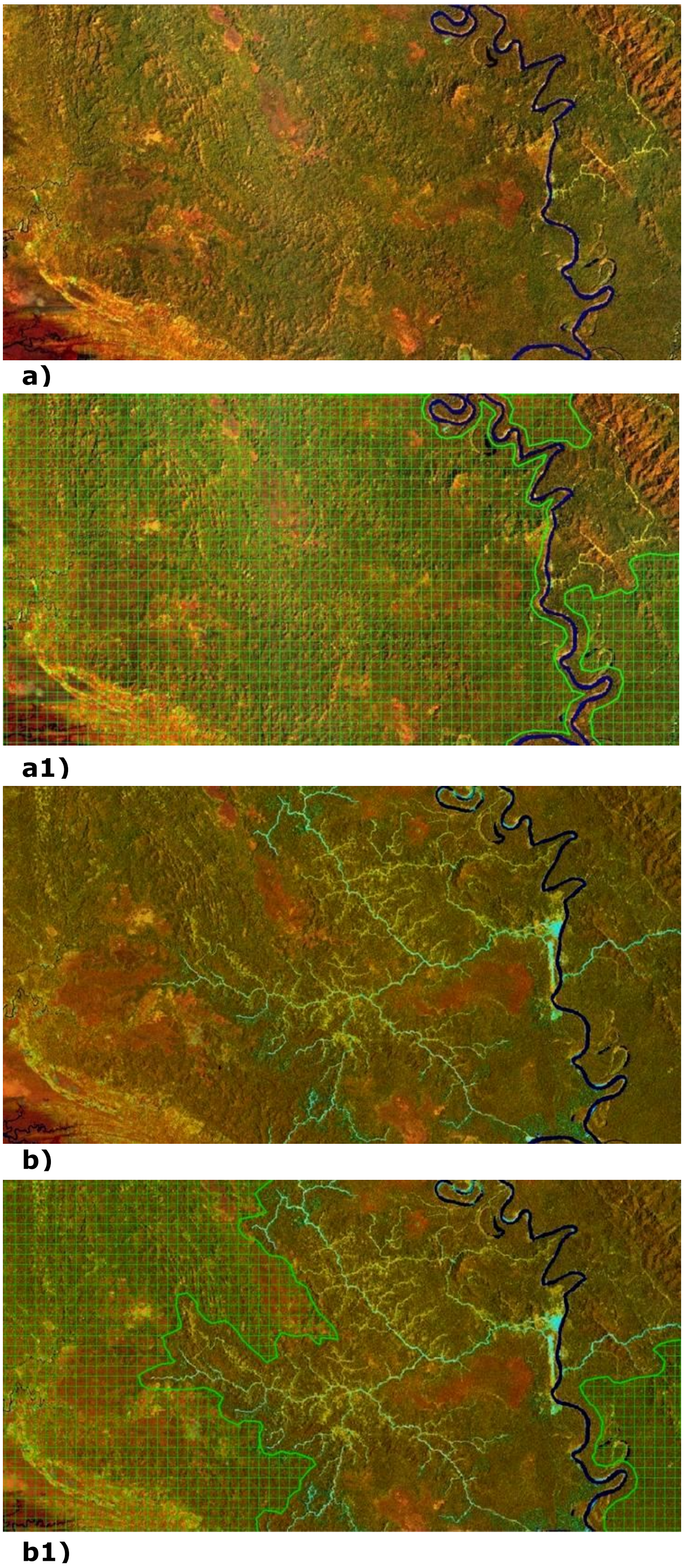


Figure 2.2.8. Forest degradation assessment in Papua New Guinea.

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 has been used to delineate intact forest boundaries.

In order to assess carbon loss 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 to non-intact forest land. Thus the total carbon loss should be equivalent to the intact forest area 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

2.2.3 Key references for Section 2.2

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2.3 ESTIMATION OF FOREST CARBON STOCKS

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2.3.1 Scope of section

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

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

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

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

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

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

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

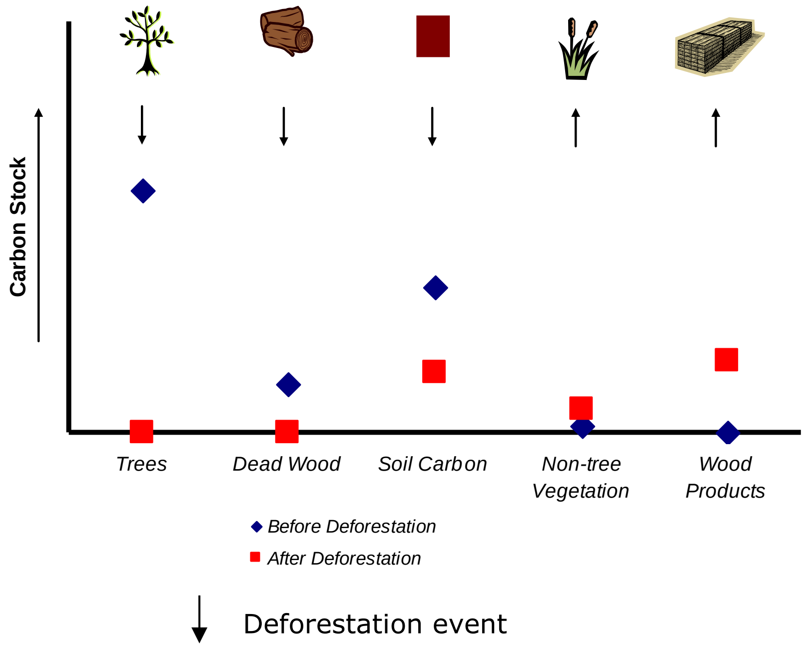
2.3.2.1 Issues related to carbon stocks

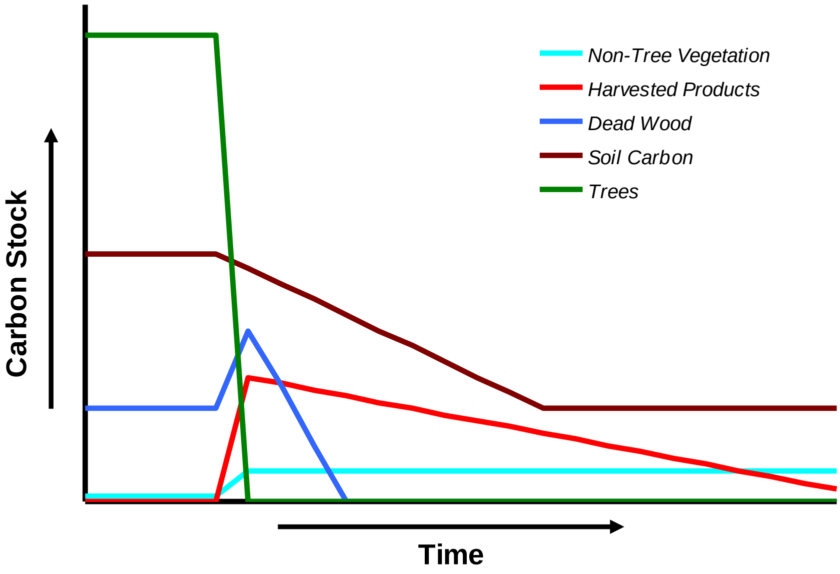
2.3.2.1.1 Fate of carbon pools as a result of deforestation and degradation

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

- In all cases, following deforestation and degradation, the stock in living trees decreases.
- Where degradation has occurred this is often followed by a recovery unless continued anthropogenic pressure or altered ecologic conditions precludes tree regrowth.
- The decreased tree carbon stock can either result in increased dead wood, increased wood products or immediate emissions.
- Dead wood stocks may be allowed to decompose over time or may, after a given period, be burned leading to further emissions.
- Wood products over time decompose, burned, or are retired to land fill.
- Where deforestation occurs, trees can be replaced by non-tree vegetation such as grasses or crops. In this case, the new land-use has consistently lower plant biomass and often lower soil carbon, particularly when converted to annual crops.
- Where a fallow cycle results, then periods of crops are interspersed with periods of forest regrowth that may or may not reach the threshold for definition as forest.

Figure 2.3.1. Fate of existing forest carbon stocks after deforestation in (sub-) tropical regions.





Note: harvested wood products do not remain the same place

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

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

2.3.3 Which Tier should be used?

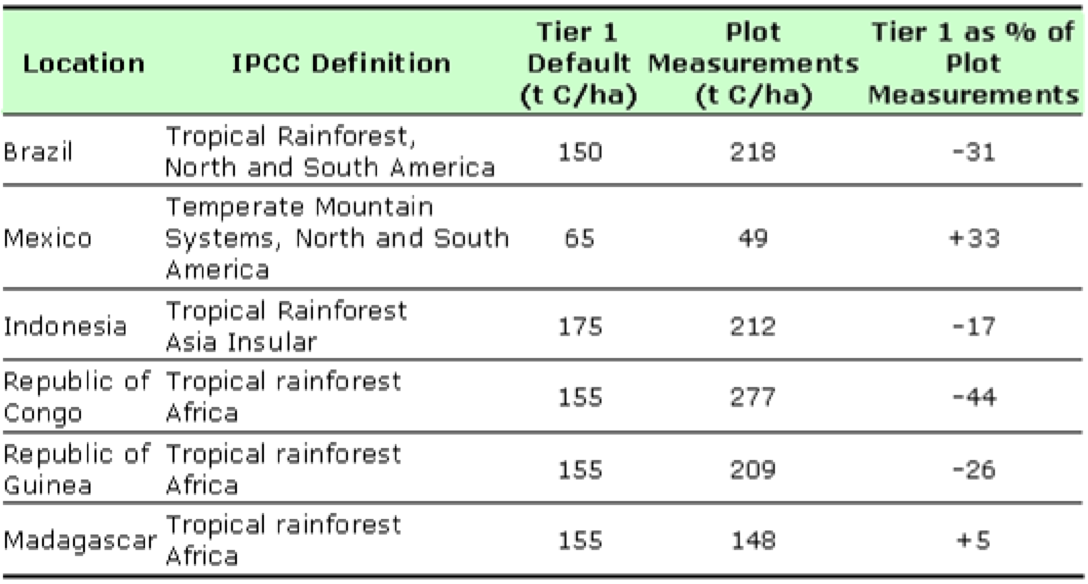
2.3.3.1 Explanation of IPCC Tiers

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

Tier 1 requires no new data collection to generate estimates of forest biomass. Default values for forest biomass and forest biomass mean annual increment (MAI) are obtained from the IPCC Emission Factor Data Base (EFDB), corresponding to broad continental forest types (e.g. African tropical rainforest). Tier 1 estimates thus provide limited resolution of how forest biomass varies sub-nationally and have a large error range (~ +/- 50% or more) for growing stock in developing countries (Box 2.3.1). The former is important because deforestation and degradation tend to be localized and hence may affect subsets of forest that differ consistently from a larger scale average (Figure 2.3.2). Tier 1 also uses simplified assumptions to calculate net emissions. For deforestation, Tier 1 uses the simplified assumption of instantaneous emissions from woody vegetation, litter and dead wood. To estimate emissions from degradation (i.e. Forest remaining as Forest), Tier 1 applies the gain-loss method (see Chapter 1) using a default MAI combined with losses reported from wood removals and disturbances, with transfers of biomass to dead organic matter estimated using default equations.

Box 2.3.1. Error in Carbon Stocks from Tier 1 Reporting

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

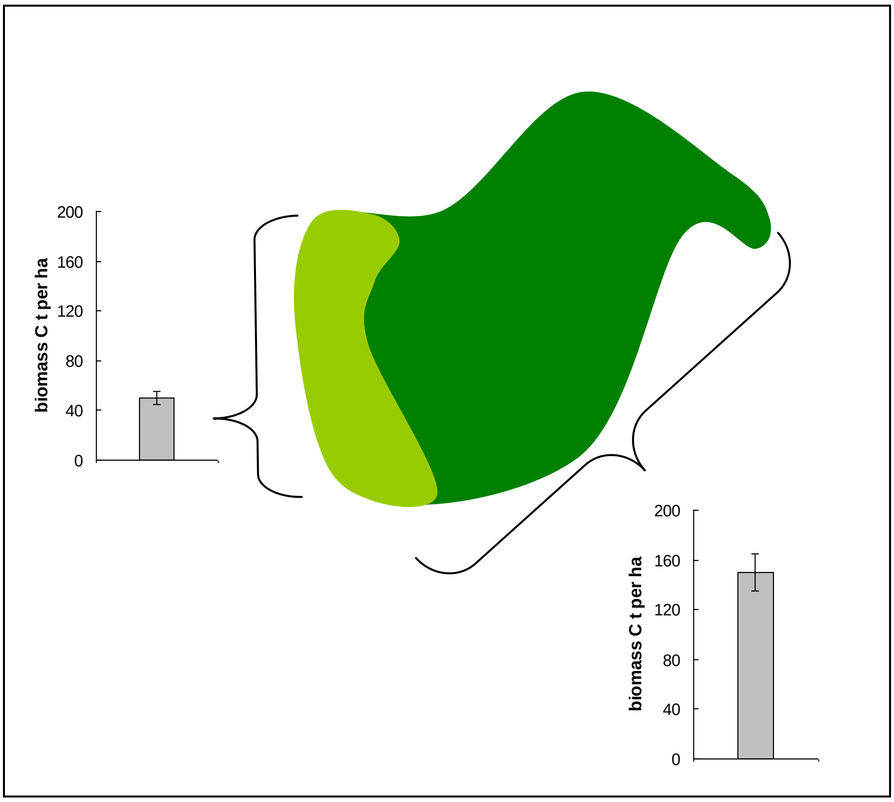


Location	IPCC Definition	Tier 1 Default (t C/ha)	Plot Measurements (t C/ha)	Tier 1 as % of Plot Measurements
Brazil	Tropical Rainforest, North and South America	150	218	-31
Mexico	Temperate Mountain Systems, North and South America	65	49	+33
Indonesia	Tropical Rainforest Asia Insular	175	212	-17
Republic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

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

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

Figure 2.3.2. A hypothetical forest area, with a subset of the overall forest, or strata, denoted in light green.



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

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

2.3.3.2 Data needs for each Tier

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

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

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

* MAI = Mean annual increment of tree growth

2.3.3.3 Selection of Tier

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

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

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

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

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

2.3.4 Stratification by carbon stocks

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

2.3.4.1 Why stratify?

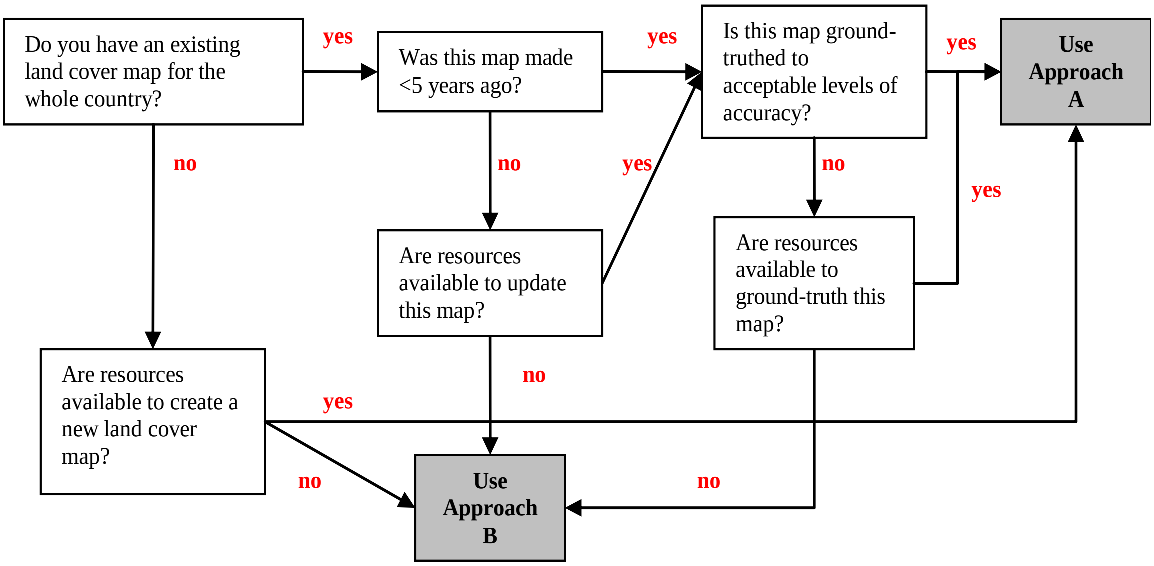
Different carbon stocks exist in different forest types and ecoregions depending on physical factors (e.g., precipitation regime, temperature, soil type, topography), biological factors (tree species composition, stand age, stand density) and anthropogenic factors (disturbance history, logging intensity).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

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

2.3.4.2 Approaches to stratification

There are two possible approaches for stratifying forests for national carbon accounting, both of which require some spatial information on forest cover within a country. In Approach A, all of a country’s forests are stratified ‘up-front’ and carbon stock estimates are made to produce a country-wide map of forest carbon stocks. At future monitoring events, only the activity data need to be monitored and combined with the pre-estimated carbon stock values. Such a map would then need to be updated periodically—at least once per commitment period. In Approach B, a full land cover map of the whole country does not need to be created. Rather, carbon estimates are made at each monitoring event only in those forests strata that have undergone change. Which approach to use depends on a country’s access to relevant and up-to-date data as well as its financial and technological resources. See Box 2.3.2 that provides a decision tree that can be used to select which stratification approach to use. Details of each approach are outlined below.

Box 2.3.2. Decision tree for stratification approach



Approach A: ‘Up-front’ stratification using existing or updated land cover maps

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

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

- When was the map created? Land cover change is often rapid and therefore a land cover map that was created more than five years ago is most likely out-of-date and no longer relevant. If this is the case, a new land cover map should be created. To participate in REDD+ activities it is likely a country will need to have at least a land cover map for a relatively recent time (benchmark map—see section 2.1).
- Is the existing map at an appropriate resolution for your country’s size and land cover distribution? Land cover maps derived from coarse-resolution satellite imagery may not be detailed enough for very small countries and/or for countries with a highly patchy distribution of forest area. For most countries, land cover maps derived from medium-resolution imagery (e.g., 30-m resolution Landsat imagery) are adequate (see section 2.1).

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

Land cover and land use maps are sometimes produced for different purposes and therefore the classification may not be fully useable in their current form. For example, a land use map may classify all forest types as one broad 'forest' category that would not be valuable for carbon stratification unless more detailed information was available to supplement this map. Indicator maps are valuable for adding detail to broadly defined forest categories (see Box 2.3.3 for examples), but should be used judiciously to avoid overcomplicating the issue. In most cases, overlaying one or two indicator maps (elevation and distance to transportation networks, for example) with a forest/non-forest land cover map should be adequate for delineating forest strata by carbon stocks, though this would need to be confirmed with field data.

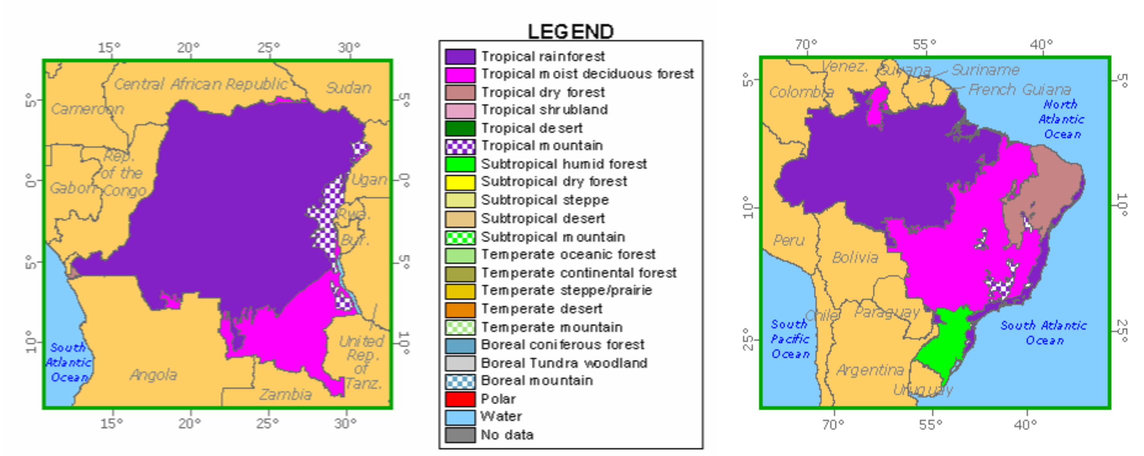
Once strata are delineated on a ground-validated land cover map and forest types have been identified, carbon stocks are estimated for each stratum using appropriate measuring and monitoring methods. A national map of forest carbon stocks can then be created (see section 2.3.4).

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

Ecological zone maps

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

1. Holdridge life zones (http://geodata.grid.unep.ch/)
2. WWF ecoregions (http://www.worldwildlife.org/science/data/terreco.cfm)
3. FAO ecological zones (http://www.fao.org/geonetwork/srv/en/main.home, type 'ecological zones' in search box)



Indicator maps

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

Biophysical indicator maps	**Anthropogenic indicator maps**
Elevation	Distance to deforested land or forest edge
Topography (slope and aspect)	Distance to towns and villages
Soils	Proximity to transportation networks

Rural population density

Areas of protected forests

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

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

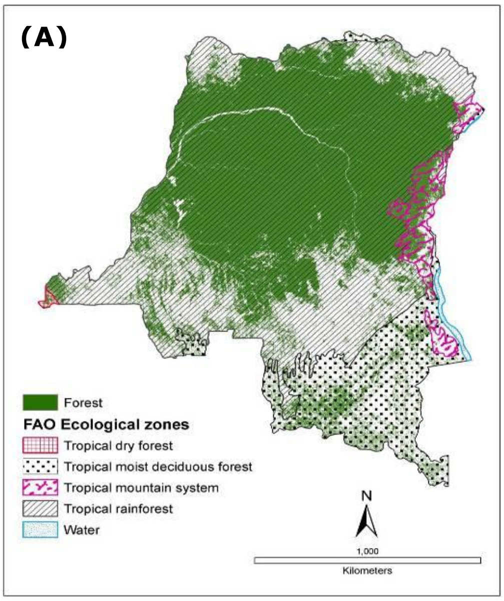
Box 2.3.4. Forest stratification in countries with limited data availability

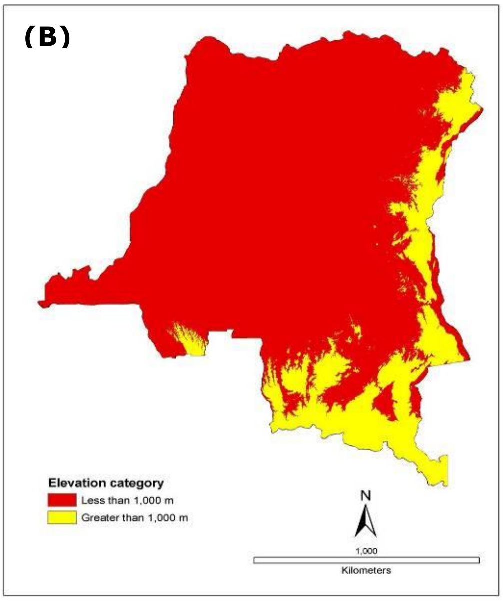
An example stratification scheme is shown here for the Democratic Republic of Congo.

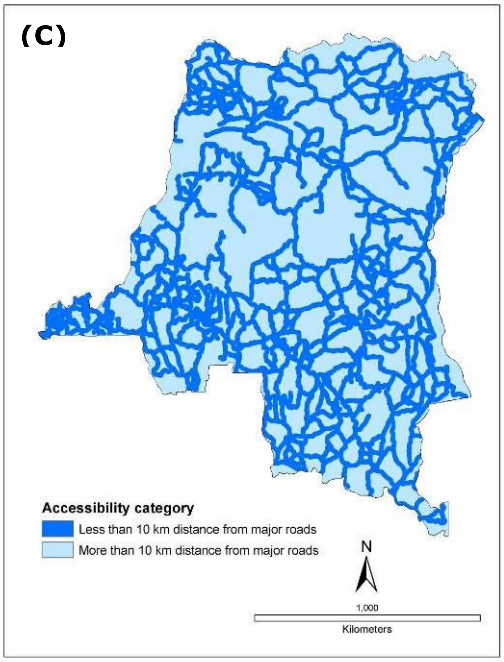
Step 1. Overlay a map of forest cover with an ecological zone map (A).

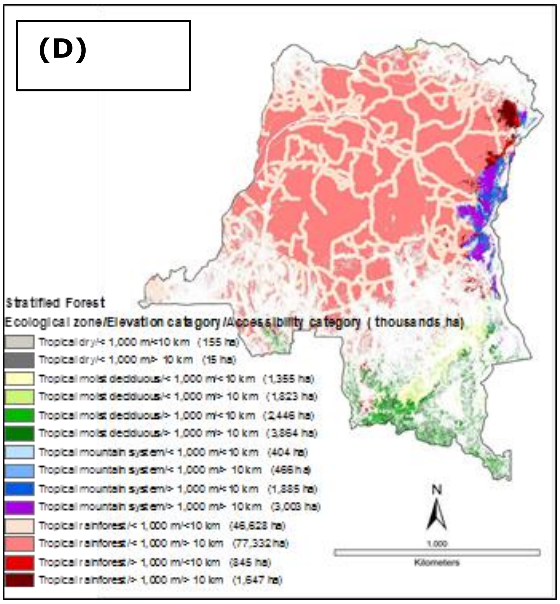
Step 2. Select indicator maps. For this example, elevation (B) and distance to roads (C) were chosen as indicators.

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









Approach B: Continuous stratification based on a continuous carbon inventory

Where wall-to-wall land cover mapping is not possible for stratifying forest area within a country by carbon stocks, regularly-timed "inventories" can be made by sampling only the areas subject to deforestation, degradation, and/or enhancement. Using this approach, a full land cover map for the whole country is not necessary because carbon assessment occurs only where land cover change occurred (forest to non-forest, or intact to degraded forest in some cases). Carbon measurements can then be made in neighbouring pixels that have the same reflectance/textural characteristics as the pixels that had undergone change in the previous interval, serving as proxies for the sites deforested or degraded, and carbon losses can be calculated.

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

2.3.5 Estimation of carbon stocks of forests undergoing change

2.3.5.1 Decisions on which carbon pools to include

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

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

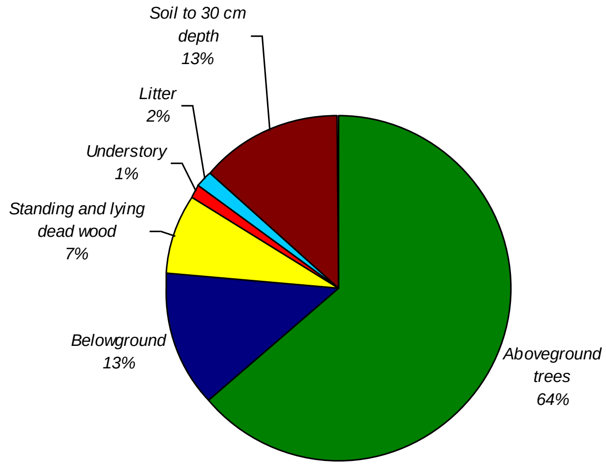
Above all is the principle of conservativeness. This principle ensures that reports of decreases in emissions are not overstated. **Clearly for this purpose both reference level and subsequent estimations must include exactly the same pools.** Conservativeness also allows for pools to be omitted except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

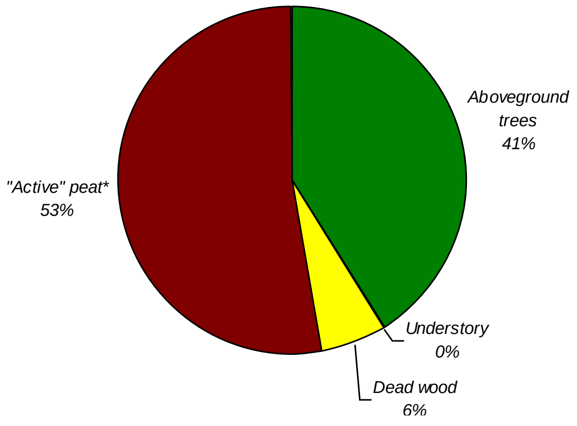
2.3.5.1.1 Key pools

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

In all cases it will make sense to include trees, as trees are relatively easy to measure and will always represent a significant proportion of the total carbon stock. The remaining pools will represent varying proportions of total carbon depending on local conditions. For example, belowground biomass carbon (roots) and soil carbon to 30 cm depth represents 26% of total carbon stock in estimates in tropical lowland forests of Bolivia but more than 50 % in the peat forests of Indonesia (Figure 2.3.3 a & b[42]). It is also possible that which pools are included or not varies by forest type/strata within a country. It is possible that say forest type A in a given country could have relatively high carbon stocks in the dead wood and litter pools, whereas forest type B in the country could have low quantities in these pools—in this case it might make sense to measure these pools in the forest A but not B as the emissions from deforestation would be higher in A than in B. In other words, which pools are selected for monitoring do not need to be the same for all forest types within a country.

Figure 2.3.3. LEFT- Proportion of total stock (202 t C/ha) in each carbon pool in Noel Kempff Climate Action project (a pilot carbon project), Bolivia, and RIGHT- Proportion of total stock (236 t C/ha) in each carbon pool in peat forest in Central Kalimantan, Indonesia (active peat includes soil organic carbon, live and dead roots, and decomposing materials).





Pools can be divided by ecosystem and land use change type into key categories (large carbon source) or minor categories (small carbon source). Key categories represent pools that could account for more than 20% of the total emissions resulting from the deforestation or degradation (Table 2.3.2).

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

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

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

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

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

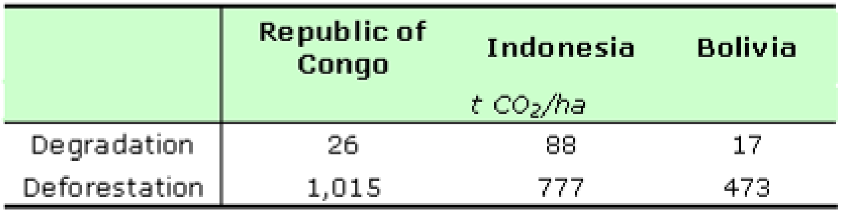
Dead wood is a key source in old growth forest where it can represent more than 10% of total biomass, but in young successional forests, for example, it will not be a key category.

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

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

Box 2.3.5. 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

(Data from unpublished data from measurements by Winrock)

2.3.5.1.2 Selecting carbon measurement pools:

Step 1: Include aboveground tree biomass

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

Step 2: Include belowground tree biomass

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

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

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

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

Step 3: Assess the relative importance of additional carbon pools

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

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

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

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

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

2.3.5.2 General approaches to estimation of carbon stocks

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

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

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

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

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

2.3.5.2.2 Step 2: Assess existing data

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

- ☐ The data are less than 10 years old
- ☐ The data are derived from multiple measurement plots
- ☐ All species must be included in the inventories
- ☐ The minimum diameter for trees included is 30cm or less at breast height
- ☐ Data are sampled from good coverage of the strata over which they will be extrapolated

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

- ☐ Forest inventory data
- ☐ Data from scientific studies

Forest inventory data

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

Stand tables—these data from a traditional forest inventory are potentially the most useful from which estimates of the carbon stock of trees can be calculated. Stand tables generally include a tally of all trees in a series of diameter classes. The method basically involves estimating the biomass per average tree of each diameter (diameter at breast height, dbh) class of the stand table, multiplying by the number of trees in the class, and summing across all classes[43]. The mid-point diameter of the class can be used[44] in combination with an allometric biomass regression equation. Guidance on choice of equation and application of equations is widely available (for example see sources in Box 2.3.8). For the open-ended largest diameter classes it is not obvious what diameter to assign to that class. Sometimes additional information is included that allows educated estimates to be made, but this is often not the case. The default assumption should be to assume the same width of the diameter class and take the midpoint, for example if the highest class is >110 cm and the other class are in 10 cm bands, then the midpoint to apply to the highest class should be 115 cm.

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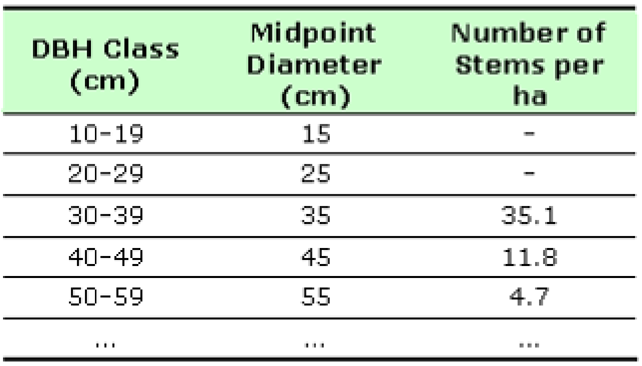
[43] More details are given in Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper 143, Rome, Italy.

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

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

Sometimes, the stand tables only include trees with a minimum diameter of 30 cm or more, which essentially ignores a significant amount of carbon particularly for younger forests or heavily logged forests. To overcome the problem of such incomplete stand tables, an approach has been developed for estimating the number of trees in smaller diameter classes based on number of trees in larger classes[45]. It is recommended that the method described here (Box 2.2.6) be used for estimating the number of trees in one to two small classes only to complete a stand table to a minimum diameter of 10 cm.

Box 2.3.6. Adding diameter classes to truncated stand tables



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

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

Ratio = 35.1/11.8 = 2.97

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

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

2.97 x 104.4 = 310.6

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

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

Biomass density can be calculated from volume over bark of merchantable growing stock wood (VOB) by "expanding" this value to take into account the biomass of the other

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

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[46]

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 2.3.4.

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

Forest type	**Growing stock volume –range (VOB, 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
- If the definition of VOB has a large minimum top diameter or the VOB is comprised of trees with particularly high basic wood density then the upper bound of the range should be used

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

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

Where VOB is the same as defined above, WD is the volume-weighted average wood density of the forest (t/m^3) and BEF is the biomass expansion factor (ratio of aboveground oven-dry biomass of trees to oven-dry biomass of inventoried volume, dimensionless).

Analysis of inventory data (VOB and with corresponding biomass estimates) showed that that BEFs are significantly related to the corresponding biomass of the inventoried volume according to the following equations[47]:

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

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

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

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

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

Forest inventories often report volumes to a minimum diameter greater than 10 cm. These inventories may be the only ones available. To allow the inclusion of these inventories, volume expansion factors (VEF) were developed[48]. 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:

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

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

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

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

Tropical broadleaf forest with a VOB30 = 100 m³/ha

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

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

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

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

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

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

Data from scientific studies

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

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

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

2.3.5.2.3 Step 3: Collect missing data

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

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

Box 2.3.8. Guidance on collecting new carbon stock data

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

1. The Food and Agriculture Organization of the United Nations has been supporting forest inventories for more than 50 years—data from these inventories can be converted to C stocks using the methods given above. However, it would be useful in the implementation of new inventories that the actual dbh be measured and recorded for all trees, rather than reporting only stand/stock tables. Application of allometric equations commonly acceptable in carbon studies[49] to such data (by plots) would provide estimates of carbon stocks with lower uncertainty than estimates based on converting volume data as described above. The FAO National Forest Inventory Field Manual is available at:

   http://www.fao.org/docrep/008/ae578e00.htm
2. Specific guidance on field measurement of carbon stocks can be found in Chapter 4.3 of GPG LULUCF and also in the World Bank Sourcebook for LULUCF available at:
   http://carbonfinance.org/doc/LULUCF_sourcebook_compressed.pdf
3. Tools to guide collection of new forest carbon stock data are available at:
   http://www.winrock.org/Ecosystems/tools.asp?BU=9086

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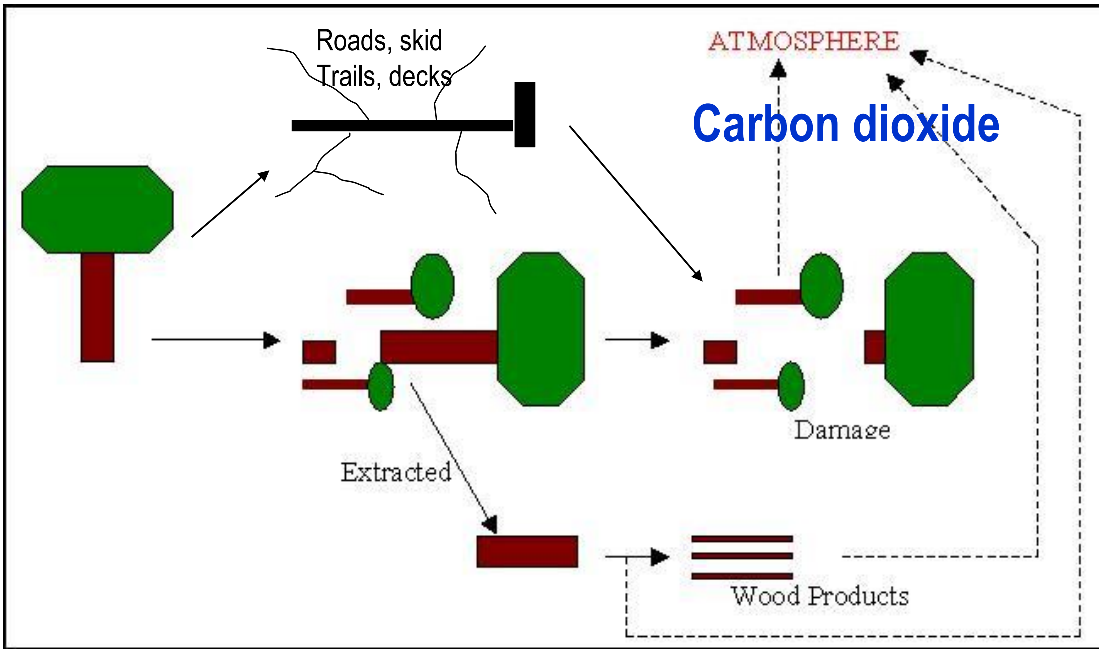
[49] E.g. Chave J et al. (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87-99.

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

Box 2.3.9. Estimating carbon gains and losses from timber extraction

A model that illustrates the fate of live biomass and subsequent CO2 emissions when a forest is selectively logged is shown below.



This model can be used for both harvesting of trees for timber or for fuel wood – in the latter case the wood products would be fuel wood or charcoal.

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

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

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

Where:

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

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

WD = wood density (t/m3)

CF = carbon fraction

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

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

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

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

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

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

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

Creating a national look-up table

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

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

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

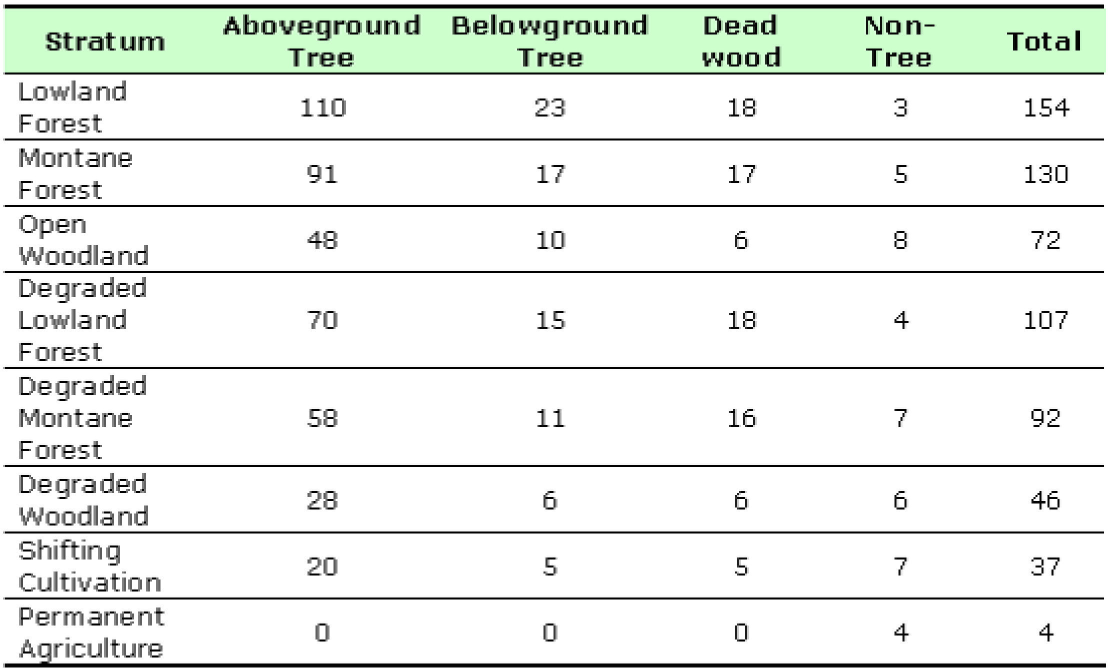
The loss for deforestation would be

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

The loss for the degradation would be

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

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



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

2.4 ESTIMATION OF SOIL CARBON STOCKS

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2.4.1 Scope of section

Section 2.4 presents guidance on the estimation of the organic carbon component of soil of the forests being deforested and degraded. Guidance is provided on: (i) which of the three IPCC Tiers should be used, (ii) potential methods for estimating changes in soil carbon stocks, and (iii) methods for estimating emissions from land use change on peat 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.

In **Section 2.4.2** explanation is provided on IPCC Tiers for soil carbon estimates.

In **Section 2.4.3** the focus is on how to generate a good Tier 2 analysis for soil carbon.

In **Section 2.4.4** guidance is given on the estimation of emissions as a result of land use change in peat swamp forests.

2.4.2 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 2.4.1). For mineral soils, the change in carbon stocks is estimated as the difference between the reference or baseline stock and the soil carbon stock after conversion. The soil carbon after conversion is calculated by applying stock change factors specific to land-use, management practices, and inputs (e.g. soil amendment, irrigation, etc.). 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 in which change in soil carbon stocks 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 and forestation 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 Section 2.4.4 for further details on this topic).

Table 2.4.1. 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 complemented by measures, 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 complemented by measures, 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.

2.4.3 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 GHG 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 Tier 1 to Tier 2. 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 2.4.2.

Table 2.4.2. 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[50] 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[51].
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.).	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

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[50] 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.).

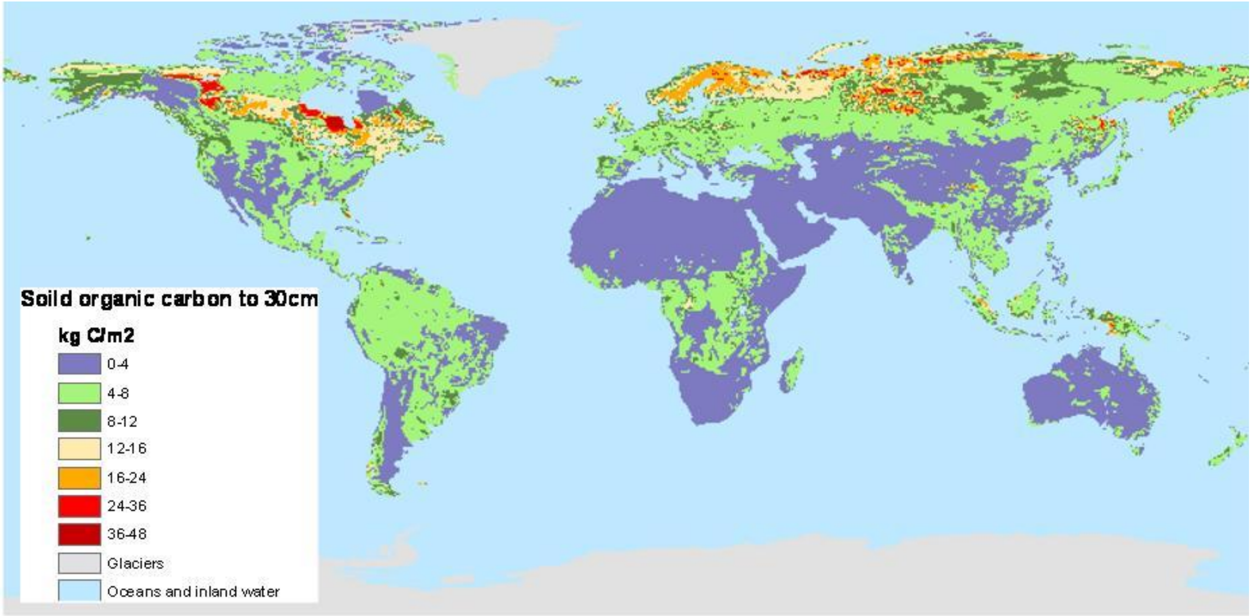
[51] Detwiler RP (1986) Land use change and the global carbon cycle: the role of tropical soils. *Biogeochemistry* 31: 1-14.

conditions globally, which means that, in at least half of the cases, use of a more 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 section 4.3 of the IPCC GPG report for more details about soil samples).

A soil carbon map is also available from the US Department of Agriculture, Natural Resources Conservation Service (Figure 2.4.1). This 0.5 degree resolution map is based on a reclassification of the FAO-UNESCO Soil Map of the World combined with a soil climate map. This map shows 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 2.4.1. Soil organic carbon map (kg/m^2 or x10 t/ha; to 30 cm depth and 0.5° resolution) from the global map produced by the USDA Natural Resources Conservation Service.



A new soil map has been recently produced under the coordination of FAO and IIASA. The map, which was released in March 2009, is referred to as the Harmonized World Soil

Database v. 1.1[52]. The map is at 1 km resolution and is reliable for Latin America, Central and Southern Africa, but uses old maps for West Africa and South Asia. It contains many soil attributes including soil carbon to 30 cm depth.

Existing map sources can be useful to countries for developing estimates for the reference level 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. Spodosols) 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[53]. 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 2.3.8). 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

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[52] FAO/IIASA/ISRIC/ISS-CAS/JRC (2009) Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria. available at: www.iiasa.ac.at/Research/LUC/luc07/External-World-soil-database/HWSD_Documentation.pdf

[53] Webb RW, Rosenzweig CE, Levine ER (2000) Global Soil Texture and Derived Water-Holding Capacities**.** 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..

applied, though they do not require representative sampling as in the development of average reference stock values.

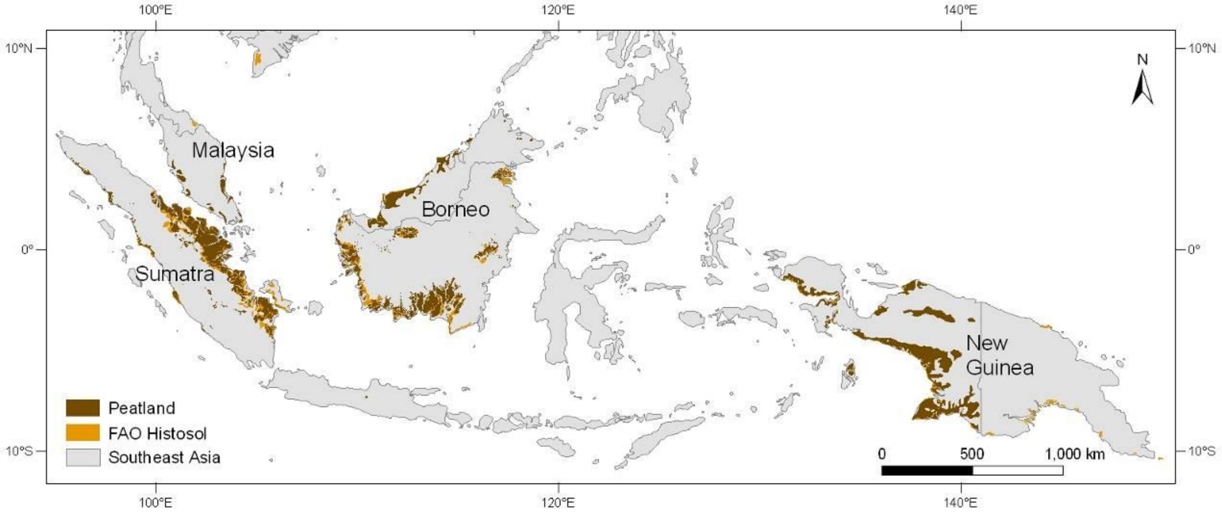
2.4.4 Emissions as a result of land use change in peat swamp forests

Deforestation of peat swamp forests (on organic soils) represents a special case and guidance is given in this section.

Tropical peat swamp forests occupy about 10% of the global peatland area, approximately 65% of the global area of tropical peat swamp forests occur in Southeast Asia (Figure 2.4.2). Peat is dead organic matter occurring largely in poorly draining environments. It forms at all altitudes and climates. In the tropics, peat is largely formed from tree and root remnants and deposits accumulate to depths up to 20 meters. If a tropical peat deposit is 10 meters thick it contains over 5,000 t/ha carbon, more than 25-fold more than that of the forest biomass growing above ground. Sequestration results when the rate of photosynthesis is larger than decomposition. Carbon sequestration range on average from 0.12-0.74 t C/ha/yr. Compared to boreal peatlands, the tropical rate is up to 4 times higher. If tropical peat is drained for agriculture or plantations it quickly decomposes, resulting in large emissions of CO_2 and N_2O to the atmosphere.

A global map of peaty soils is available from FAO (FAO-UNESCO Soil Map of the World). Wetlands International has published detailed maps on the distribution of peat swamp forests and the quantity of carbon stored in the peat for Sumatra, Kalimantan and West Papua based on maps, land surveys and satellite imagery[54].

Figure 2.4.2. Extent of lowland peat forests in Southeast Asia. The Wetlands International data have higher spatial detail and hence accuracy than the FAO data.



Emissions factors (EF) for calculating carbon emissions from peat swamp forests for REDD+ at a Tier 2 or 3 level requires site-specific data. A recent literature review questions the accuracy and usefulness of existing Tier 1 EF for operational use. Long

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[54] Wetlands International (2007). http://www.wetlands.or.id/publications_maps.php

term measurements or well established proxies will need to be put in place to support Tier 2 and 3 methodologies. Countries with significant peat swamp forest will need to develop national data to estimate and report the CO_2 and non-CO_2 emissions resulting from land use and land use changes on these areas.

In the past two decades large areas of peat swamp forests in Southeast Asia have been destroyed by logging, drainage and fire. Compared to the aboveground emissions that result from clearing the forest vegetation, emissions from peat are significantly larger from drainage and fire and continue through time because drainage causes a lowering of the water table, allowing biological oxidation of the peat (Figure 2.4.3). Both processes cause significant emissions of GHG gases. Although the area of tropical peatlands in Indonesia is only about 1.5% that of the global land surface, uncontrolled burning of peat there in 1997 emitted 2.0-3.5 Gt CO_2 equivalent or some 10% of global fossil fuel emissions for the same year[55]. Emission estimates from peat fires require Tier3 and currently have great uncertainties, because:

- ☐ Various gases and compounds and relative fractions of these will be emitted depending on fire severity, water table, peat moisture and peat type
- ☐ The combusted peat volume depends on water table level and peat moisture
- ☐ Fire intensity and burn depth depend on land cover type and previous fire history.
- ☐

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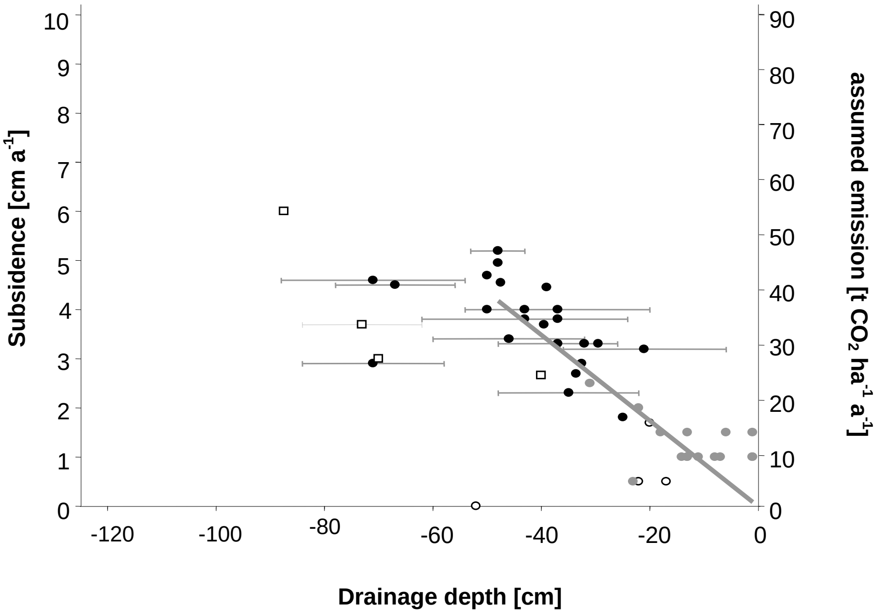
[55] Page SE, Siegert F, Rieley JO, Boehm HDV, Jayak A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature.* 420:61-65.

van der Werf GR, et al. (2004). Continental-Scale Partitioning of Fire Emissions During the 1997 to 2001 El Niño/La Niña Period. *Science*. 303: 73 - 76

Figure 2.4.3. Relation between drainage depth and CO_2 emissions from peat decomposition in tropical peat swamps[56]. Rate of subsidence in relation to mean annual water level below surface Horizontal bars indicate standard deviation in water table (where available). Open circles denote unused, drained forested sites. Land use: (□) agriculture, (●) oil palm (recorded 13 to 16 or 18 to 21 years after drainage), (●) degraded open land in the Ex Mega Rice Project area, recorded ~10 to ~12 years after drainage, (○) drained forested plots, recorded ~10 to 12 years after drainage. The slope of the line represents 0.9 t CO2/ha emitted per 1 cm drained.



The IPCC guidelines provide limited guidance for estimating GHG emissions from peat fires because peat fires are different from forest fires due to oxygen limitation and the smoldering nature of combustion. Burn history and land cover can quite easily be measured by sensors on satellites, but burn depth assessment requires field and/or LIDAR measurements and the determination of gas composition requires laboratory combustion experiments and field measurements. The depth of the water table and moisture content are key variables that control both decomposition and fire risk and to accurate measurements are needed (e.g. using dip wells) to estimate emissions.

Emissions of CO_2 via oxidation begin when either the peat swamp forest is removed and/or the water table is lowered due to drainage for agriculture or logging purposes. Most carbon is released in the form of CO_2 in an aerobic layer near the surface by decomposition. Suitable long term measurements of at least a year are required to assess emission rates under differing water management regimes. Very few such measures exist today. Couwenberg et al. (2009) showed that cleared and drained peat swamp forests emit in the range of 9 t CO_2 ha^{-1}yr^{-1} for each 10 cm of additional drainage depth. If the water table is lowered by of 0.4 meters by draining, CO_2 emissions are estimated at 35 tons CO_2per hectare per year (Figure 2.4.3).

Two important non-CO_2 greenhouse gases produced by organic matter decomposition are methane CH_4 and nitrous oxide N_2O with the latter more important due to its large global warming potential. Emissions of N_2O from tropical peats are low compared to CO_2, but evidence suggests that N_2O, emissions increase following land use change and drainage. The determination of GHG emission factors for drained peat require rigorous

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[56] Couwenberg J, Dommain R, Joosten H (2009) Greenhouse gas fluxes from tropical peatlands in Southeast Asia. Global Change Biology, in press

flux measurements by chambers or eddy covariance measurements in combination with continuous monitoring of site conditions.

The role of tropical peat is crucial in terms of GHG emissions because the carbon stock of peat considerably outweighs that of the biomass above ground. Moreover significant amounts of carbon are released by fire and decomposition.

2.5 METHODS FOR ESTIMATING CO2 EMISSIONS FROM DEFORESTATION AND FOREST DEGRADATION

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2.5.1 Scope of section

This section describes the methodologies that can be used to estimate carbon emissions from deforestation, forestation, and forest degradation. It builds on Section 2.1, 2.2 and 2.3 of this Sourcebook, which describe procedures for collecting the input data for these methodologies, namely areas of land use and land-use change (Section 2.1), and carbon stocks and changes in carbon stocks (Section 2.2 and 2.3).

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[57] 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 Section 2.2 and 2.3).

For the purposes of this Sourcebook, five IPCC land-use subcategories are relevant. The term deforestation within the REDD+ context is likely to be encompassed by the four land-use change subcategories defined for conversion of forests to non-forests (see Section 1.2.3[58]). 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

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[57] 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.

[58] 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 section.

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 Section 2.3). 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 Section 2.3, REDD+ accounting schemes may or may not include all carbon pools. Which pools to include will depend on decisions that could be driven by such factors as financial resources, availability of existing data, ease and cost of measurement, and the principle of conservativeness.

2.5.2 Linkage to 2006 IPCC Guidelines

Table 2.5.1 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 sections: a generic methods section (Chapter 2) and the land-use category section 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 sections.

Table 2.5.1. 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 sections 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 sections (i.e., Chapter 4, 5, 6, 7, 8, or 9) of the AFOLU Guidelines (Volume 4).

2.5.3 Organization of section

The remainder of this section discusses carbon emission estimation for deforestation, forestation and forest degradation:

- **Section 2.5.4** 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 2.5.5** describes methods for estimating carbon emissions from deforestation and forestation 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 to/from forests.
- **Section 2.5.6** describes methods for estimating carbon emissions from forest degradation based on the IPCC methods for "Forest Land Remaining Forest Land."
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2.5.4 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.[59]

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 2.5.1). 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 2.5.2). Gains in the living biomass pool result from vegetation growth while in the other pools only by 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

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[59] 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).

available. In reality, a mix of the stock-difference and gain-loss approaches can be used as discussed further in this section.

Equation 2.5.1

Annual Carbon Stock Change in a Given Pool as an Annual Average Difference in Stocks

(Stock-Difference Method)

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

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 2.5.2

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 deforestation, forestation, and forest degradation, and can apply to all carbon pools.[60] 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 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 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, forested, 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 2.4.2) is not likely to be useful for deforestation or forestation estimating with a Tier 1 or Tier 2 method, but could be used for Tier 3 approach for biomass and dead organic matter

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[60] 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 in section 2.3.6.

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, fuel wood removals, and transfers to the dead organic matter pool due to disturbance. Dead 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.

2.5.5 Estimation of emissions from deforestation

2.5.5.1 Disturbance matrix documentation

Land-use conversion, particularly from forests to non-forests, can involve significant transfers of carbon among pools (no further discussion on forestation is included in this section as great detail exist in the IPCC GPG for LULUCF report). The immediate impacts of land conversion on the carbon stocks for each forest stratum can be summarized in a matrix that describes the retention, transfers, and releases of carbon in and from the pools in the original land-use due to conversion (Table 2.5.2). 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 2.3.2 in Section 2.3). 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 2.5.2. 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	▨	▨	▨	▨		▨		

2.5.5.2 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 for the gradual carbon loss during a transition period to a new steady-state system and the carbon gains due to vegetation regrowth, if any.

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 2.5.3 (below) is the equation presented in the AFOLU Guidelines for biomass.

Equation 2.5.3

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 2.5.2) 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 fuel wood, 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 sections 2.3.5 and 2.3.6). 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 2.5.1), with the time interval the period between land-use conversion and steady-state under the new land use.

2.5.5.3 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 2.5.4). (The first part of Equation 2.4.4 [for $\Delta C_{\text{Mineral}}$] 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 2.5.4

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 section 4.4.3). Default stock change factors can be found in the land-use category sections 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 2.5.5). However, empirical data from many studies on peat swamp soils in Indonesia could be used in such cases—see section 2.4.4 for further details.

Equation 2.5.5

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.

2.5.6 Estimation of emissions from forest degradation

For degradation, the main changes in carbon stocks occur in the vegetation (see Table 2.3.2 in Section 2.3). As is discussed in Section 2.4.4, estimation of soil carbon emissions is only recommended for intensive practices that involve significant soil disturbance. Selective logging for timber or fuel wood, 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 Section 2.4.4). However, in this section guidance is provided only for the emissions from biomass.

The AFOLU Guidelines recommend either a stock-difference method (Equation 2.5.1) or a gain-loss method (Equation 2.5.2) 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, fuel wood removals, and transfers of live to the dead organic matter pool due to disturbance (also see Box 2.3.9 in Section 2.3.5 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.

From a practical perspective, there are some technical challenges that would favour the use of the gain loss method for degradation, particularly for timber harvesting practices where the amount of extracted timber volume is <40 m^3/ha or so. One of the main problems with this approach is that two relatively large C pools are being compared (unless the timber extraction is very intensive and damaging), and although the error on each pool could be small, the error on the difference, expressed as a percent, would be much larger. Another issue is that timber extraction of <40 m^3/ha or so translates to <5 trees/ha in many humid tropical forests and even with the associated damage from skid trails it is possible that a very large number of plots would be needed to ensure the adequate sampling of the loss in carbon from the extracted trees and damaged forest.

Although estimating the carbon impacts of logging lend itself more readily to the gain-loss approach, estimating the carbon impacts of degradation by fire may lend itself more readily to the stock-difference approach.

For Forests Remaining Forests, the Tier 1 assumption is that net carbon stock changes in dead organic matter 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 2.5.2 above.

2.6 METHODS FOR ESTIMATING GHG EMISSIONS FROM BIOMASS BURNING

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2.6.1 Scope of section

Chapter 2.6 is focused on fires in forest environments and how to calculate greenhouse gas emissions due to vegetation fires, using available satellite-based fire monitoring products, biomass estimates and coefficients.

Section 2.6.2 introduces emissions due to fire in forest environments and approaches to estimates emissions from fires.

Section 2.6.3 focuses on the IPCC guidelines for estimating fire-related emission.

Section 2.6.4 focuses on Systems for observing and mapping fire.

Section 2.6.5 describes the potential use of existing fire and burned area products.

2.6.2 Introduction

2.6.2.1 REDD+ and emissions due to fire in forest environments

Fire is the most important disturbance agent worldwide in terms of area and variety of biomes affected, a major mechanism by which carbon is transferred from the land to the atmosphere, and a globally significant source of aerosols and many trace gas species. Wildfires operate on all continents apart from Antarctica, globally consuming on average perhaps 5% of net annual terrestrial primary production (Randerson et al., 2005), and taking into account below ground peat fires, are estimated, on average, to emit an amount of carbon equivalent to 2 Pg C per annum (van der Werf et al., 2010). This is equivalent to about 20% of global emissions from fossil fuels (Bernstein et al., 2007).

On the other hand fire is an integral part of many ecosystems. Many plant species in naturally fire-affected ecosystems require fire to germinate, to establish, and/or to reproduce. Fire suppression not only eliminates these species but can also lead to the buildup of inflammable debris and the creation of less frequent but much larger and destructive wildfires. Fire management is therefore essential to maintaining the health of fire-affected ecosystems.

Reducing the emissions from deforestation and degradation (REDD) from fire requires an understanding of the process of fire in forest systems (either as an ecological change agent, a disturbance, a forest management tool, or as a process associated with land cover conversion) and how fire emissions are calculated. Fire can be seen both as a threat to REDD, in the measure in which it is a disturbance affecting areas where programs aimed at reducing deforestation and degradation are in place, but also as an integral component of REDD+ if the emissions due to fire are directly addressed through integrated fire and forest management programs. The specific details of how REDD+ will be implemented with respect to fire are still in development.

This chapter focuses on above-ground fires in forest environments and how to calculate greenhouse gas emissions due to vegetation fires, using available satellite-based fire monitoring products, biomass estimates and coefficients. Below-ground fires, for example, those that occur in the peat forests of Indonesia are major sources of emissions from biomass burning under drought conditions (van der Werf et al 2010, Page et al 2012) and along with high latitude peats (Russia, Alaska, Canada) may become even greater sources under future climate change. However, below-ground fires are beyond the scope of this sourcebook version. It is envisaged that in the future, below-ground fires will be accounted for.

The effects of fire in forests are widely variable. It is possible to refer to fire severity as a term to indicate the magnitude of the effects of the fire on the ecosystem[61] which in turn is strongly related to the post-fire status of the ecosystem. As a broad categorization, low severity surface fires affect mainly the understory vegetation rather than the trees, while high severity crown fires directly affect the trees. The latter are sometimes referred to as stand replacement fires. Consequently, at the broad scale, ground fires generally do not alter the equilibrium of the ecosystem (i.e. do not result in a conversion from forest to non-forest cover), but increased fire frequency and intensity can lead to forest transition, starting with degradation before complete conversion. Crown fires can lead to a forest-non-forest temporary transition followed by regrowth (i.e. fire is a disturbance), or to a permanent change where human activities inhibit forest regeneration.

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[61] De Santis A, Chuvieco E, Vaughan P (2009) Short-term assessment of burn severity using the inversion of PROSPECT and GeoSail models. *Remote Sensing of Environment.* 113: 126-136.

The issue of the definition of forest (described in detail in chapter 1.2) is a particularly sensitive one when the fire monitoring from satellite data is concerned. Within the 10 to 30 percent tree crown cover range indicated by the Marrakesh Accords, most of woody savannah ecosystems might or might not be considered as forest. These are the ecosystems where most of the biomass burning occurs (Roy et al., 2008, van der Werf, 2010) and where fire is an important process contributing to the maintenance of the present land cover. Typically, high fire frequency in savannas (fire return interval of a few years or less) inhibits young tree growth and succession from open to closed woodland ecosystems. These fire-prone ecosystems are characterized by a cycle of recurring fires and natural regeneration of the vegetation to its original state; therefore, the presence of fire is not *per se* regarded as a component of the climate change process. Instead, there is a need to establish baseline data on the current fire regimes, in order to assess any changes and trends in fire and emission patterns.

Different fire management practices in different ecosystems can determine the amount of trace-gas and particulate emissions and changes to forest carbon stocks. In closed forests, controlled ground fires reduce the amount of biomass in the understory but, over a period of time, may lead to increase in carbon stock by reducing the occurrence of high severity, stand replacement fires, and under certain circumstances, by promoting the growth of fast growing shade intolerant tree species. Conversely, in open woodland systems, reducing the occurrence of fire allows tree growth with the subsequent effect of carbon sequestration. Furthermore, emission coefficients do have a seasonal variability (Korontzi et al., 2004, Meyer et al., 2012): even assuming that fires affect the same areal extent, shifting the timing of the burning (early season versus late season) can have a significant effect on the total emissions. Wildfires are characterised by two main forms of combustion– flaming and smouldering combustion; which implies that variable emission coefficients should be used. It is the relative mix of these two types of combustion that generate the mix of species emitted from biomass burning. Flaming combustion or oxidation-type combustion reactions (e.g. production of CO_2, NOx) proceed at a faster rate when the fuel is dry and has a large surface-area-to-volume (SAV) ratio. The converse holds for smoldering combustion or reduction-type reactions (CO, CH_4 etc). A good example is the tropical savannas in which early dry season burns produce a higher CO/CO_2 ratio than those during the late dry season. Early season burning when fuels tend to be moist is often recommended as a good fire management practice in savanna woodlands as the fires are less intense, thus less damaging to the trees, the ecosystem and hence the carbon stock. In order to fully quantify the implications in terms of emissions of early versus late season fires, more research is needed to characterize fully the seasonal variability of the emission coefficients. The purpose of this chapter is to present and explain the IPCC guidelines, list the available sources of geographically distributed data to be used for the emissions estimation, illustrate some of the main issues and uncertainties associated with the various steps of the methodology. Drawing from the experience of GOFC-GOLD Fire Implementation Team and Regional Fire Networks, the chapter emphasizes the possible use of satellite derived products and information.

2.6.2.2 Direct and indirect approach to emission estimates

Estimates of atmospheric emissions due to biomass burning have conventionally been derived adopting ‘bottom up’ inventory based methods (Seiler & Crutzen, 1980) as:

$$L = A \times Mb \times Cf \times Gef \qquad [\textbf{Equation 2.6.1}]$$

where the quantity of emitted gas or particulate L [g] is the product of the area affected by fire A [m2], the fuel loading per unit area Mb [g m^{-2}], the combustion factor Cf, i.e. the proportion of biomass consumed as a result of fire [g g^{-1}], and the emission factor or emission ratio Gef, i.e. the amount of gas released for each gaseous specie per unit of biomass load consumed by the fire [g g^{-1}].

Rather than attempting to measure directly the emissions L, this method estimates the pre-fire biomass (A x Mb), then estimate what portion of it burned (Cf) and finally converts the total biomass burned (A x Mb x Cf) into emissions by means of the coefficient Gef. For this reason, it is defined as an indirect method. A precise estimate of L requires a precise estimate of all the terms of equation 2.6.1.

In the past, the area burnt (A) was considered to be the variable with the greatest uncertainty, however, in the last decade significant improvements in the systematic mapping of area burned from satellite data have been made (Roy et al. 2008). Fuel load (Mb) remains an uncertain variable and has been generally estimated from sample field data, and/or simulation models of plant productivity driven by satellite-derived estimates of plant photosynthesis. The CASA model is a good example of this approach where by satellite data is used to calculate Net Primary Production to provide biomass increments and partitioning between fuel classes[62]. Emission factors (Gef) have been fairly precisely estimated from laboratory measurements[63]. However it is by no means certain how these translate to different conditions outside those measured in the laboratory and at the ecosystem level. Aerosol emission factors and the temporal dynamics of emission factors as a function of fuel moisture content remain uncertain (e.g. those of CO2 versus CO, see above). The burning efficiency (Cf) is a function of fire condition/behavior, the relative proportions of woody, grass, and leaf litter fuels, the fuel moisture content and the uniformity of the fuel bed. Dependencies on cover type can potentially be specified by the use of satellite-derived land cover classifications or related products such as the percentage tree cover product[64], used by Korontzi et al. (2004) to distinguish grasslands and woodlands in Southern Africa through a model related to Cf (combustion completeness, CC) as a weighted proportion of fuel types and emission factor database values. Roy and Landmann[65] stated that there is no direct method to estimate CC from remote sensing data, although for savannas they demonstrated a near linear relationship between the product of CC and the proportion of a satellite pixel affected by fire and the relative change in short wave infrared reflectance.

Rather than estimate A × Mb × Cf independently, a more recently proposed alternative is to directly measure the power emitted by actively burning fires and from this estimate the total biomass consumed. The radiative component of the energy released by burning vegetation can be remotely sensed at mid infrared and thermal infrared wavelengths[66,67]. This instantaneous measure, the Fire Radiative Power (FRP) expressed in Watts [W], has been shown to be related to the rate of consumption of biomass [g/s]. Importantly this method provides accurate (i.e. ± 15%) estimates of the rate of fuel consumed (Wooster et al 2005) and the integral of the FRP over the fire duration, the Fire Radiative Energy (FRE) expressed in Joules [J], has been shown to be linearly related to the total biomass consumed by fire [g][68]. However, the accuracy of the integration of FRP over time to derive FRE depends on the spatial and temporal sampling of the emitted power. Ideally,

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[62] van der Werf GR et al. (2006) Interannual variability in global biomass burning emissions from 1997 to 2004. *Atmospheric Chemistry and Physics.* 6: 3423-3441.

[63] Andreae MO, Merlet P (2001) Emission of trace gases and aerosols from biomass burning, *Global Biogeochemical Cycles*, 15: 955-966.

[64] Hansen MC et al. (2002) Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the MODIS Vegetation Continuous Field Algorithm. *Earth Interactions*, 7:1-15.

[65] Roy DP, Landmann T (2005) Characterizing the surface heterogeneity of fire effects using multi-temporal reflective wavelength data. *International Journal of Remote Sensing*, 26:4197-4218.

[66] Ichoku C, Kaufman Y (2005) A method to derive smoke emission rates from MODIS Fire Radiative Energy Measurements. *IEEE Transaction Geosciences & Remote Sensing*, 43: 2636-2649.

[67] Smith AMS, Wooster MJ (2005), Remote classification of head and backfire types from MODIS fire radiative power observations. *International Journal of Wildland Fire*. 14, 249-254.

[68] Freeborn PH et al. (2008) Relationships between energy release, fuel mass loss, and trace gas and aerosol emissions during laboratory biomass fires*. J. Geophys. Res.,* 113, D01102

the integration requires high spatial resolution and continuous observation over time, while the currently available systems provide low spatial resolution and high temporal resolution (geostationary satellites) or moderate spatial resolution and low temporal resolution (polar orbiting systems). Only recently FRP has begun to be integrated in operational systems for GHG estimation: among these, the Global Fire Assimilation System (GFASv1.0) which calculates biomass burning emissions by assimilating FRP observations from the MODIS instruments (Terra and Aqua satellites) (Kaiser et al 2012). GFAS corrects for gaps in the observations (cloud cover, spurious FRP observations of volcanoes, gas flares and other industrial activity), calculates combustion rates with land cover-specific conversion factors, uses emission factors for 40 gas-phase and aerosol trace species based on the literature, and calculates daily emissions on a global 0.5_×0.5_ grid from 2003 to the present.

2.6.3 IPCC guidelines for estimating fire-related emission

The IPCC guidelines include the use of an indirect method for emissions estimates, and include a three tiered approach to CO2 and non-CO2 emissions from fire, Tier 1 using mostly default values for equation 2.6.1, and Tiers 2 and 3 including increasingly more site-specific formulations for fuel loads and coefficients.

Using the units adopted in the IPCC guidelines, equation 2.6.1 is written as:

$$Lfire = A \times Mb \times Cf \times Gef \times 10^{-3} \qquad [\textbf{Equation 2.6.2}]$$

where L is expressed in tonnes of each gas
A in hectares
Mb in tonnes/hectare
Cf is dimensionless
Gef in grams/kilogram

The Area burned A [ha] should be characterised as a function of forest types of different climate or ecological zones and, within each forest type, characterised in terms of fire characteristics (crown fire, surface fire, land clearing fire, slash and burn...). This is needed to parameterize appropriately the Cf × Ge factors, which might change with the type of fire.

In Tier 1, emissions of CO_2 from dead organic matter are assumed to be zero in forests that are burnt, but not fully destroyed by fire. If the fire is of sufficient intensity to destroy a portion of the forest stand, under Tier 1 methodology, the carbon contained in the killed biomass is assumed to be immediately released to the atmosphere. This Tier 1 simplification may result in an overestimation of actual emissions in the year of the fire, if the amount of biomass carbon destroyed by the fire is greater than the amount of dead wood and litter carbon consumed by the fire. Non-CO_2 greenhouse gas emissions are estimated for all fire situations. Under Tier 1, non-CO_2 emissions are best estimated using the actual fuel consumption provided in AFOLU Table 2.4, and appropriate emission factors (Table 2.6) (i.e., not including newly killed biomass as a component of the fuel consumed).

For Forest Land converted to other land uses, organic matter burnt is derived from both newly felled vegetation and existing dead organic matter, and CO_2 emissions should be reported. In this situation, estimates of total fuel consumed (AFOLU Table 2.4) can be used to estimate emissions of CO_2 and non- greenhouse gases using equation 2.6.2.

In the case of Tier 1 calculations, AFOLU Tables 2.4 through 2.6 provide the all the default values of Mb [t/ha], Cf [t/t] and Gef [g/kg] to be used for each forest type according to the fire characteristics. Tier 2 methods employ the same general approach as Tier 1 but make use of more refined country-derived emission factors and/or more refined estimates of fuel densities and combustion factors than those provided in the default tables. Tier 3 methods are more comprehensive and include considerations of the dynamics of fuels (biomass and dead organic matter).

2.6.4 Mapping fire from space

2.6.4.1 Systems for observing and mapping fire

Fire monitoring from satellites falls into three primary categories, detection of active fires, mapping of post fire burned areas (fire scars) and fire characterization (e.g. fire severity, energy released). For the purposes of emission estimation we are primarily interested in the latter two categories. Nonetheless, rather than for emission inventories, the detection of active fires may be useful in terms of assessing fire history and the effectiveness of REDD+ related fire management activities. Satellite data can also contribute to early warning systems for fire (providing information on vegetation type and condition, and combining it into fire danger rating) and to validate fire risk assessment systems which can then be used to better manage fire but these aspects would fall beyond the scope of this chapter. Satellite systems for Earth Observation are currently providing data with a wide range of spatial resolutions. Using the common terminology, the resolution can be classified as:

- Fine or Hyperspatial (1-10 meter pixel size). Examples: Ikonos, , Quick Bird, SPOT-5 HRG, Formosat
- Moderate or High Resolution[69]: pixel size from 10 to 100 meters. Example: SPOT-4 HRG, Landsat TM/ETM, CBERS MMRS, Sentinel-2 (2A launched in June 2015)
- Coarse resolution: pixel size over 100 meters. Examples: VIIRS, MODIS, MERIS (acquisition stopped in 2012), SPOT-VGT, AVHRR, Sentinel-3 (launch expected for 2015)

Although still belonging to the research domain, SAR radar data have a potential for complementing optical data in environments with persistent cloud cover, such as some boreal and tropical regions,

The wide range of possible REDD+ fire applications pose different requirement to the satellite data used to assess the fire activity. Compiling national fire emission inventories, monitoring the changes in fire seasonality and patterns due to fire management or assessing the area affected by fire in a protected forested area are all activities that might fall under REDD+ fire, and that can be supported by satellite data and products. However, the type of information needed is different and can be provided by different combinations of the available earth observation satellites.

While in principle only hyperspatial and, to some extent, high resolution data can provide the sub-hectare mapping required for local scale REDD+ applications, the tradeoffs between spatial, radiometric, spectral and temporal resolution of satellite systems need to be taken into account. Higher resolution images have a low temporal resolution (15-20 days in the case of Landsat-class sensors) and non-systematic acquisition (especially the hyperspatial sensors). Combined with missing data from these optical systems due to cloud cover, the data availability of each sensor taken individually is, in most if not all circumstances, inadequate to monitor an inherently multi-temporal phenomenon like fire. Provided that the burned areas are visible for a significant period of time (at least one or two months), combining data from more than one sensor can provide sufficient coverage for high resolution mapping of sub-continental areas. The recent availability of

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[69] Traditionally Landsat and SPOT data have been referred to as 'high' spatial resolution. The use of the term moderate resolution to include Landsat class observation is a relatively new development but is not common in the literature.

IRS AWiFS data with 3-5 acquisitions each month at c. 60m resolution raises the possibility of increased temporal resolution at moderate/high spatial resolution. The DMC constellation also provides a potentially useful data source, with improved temporal resolution and high spatial resolution, although the data is limited to the visible and near infrared bands of the spectrum.

Moreover, for technological and commercial reasons hyperspatial sensors are not optimal for fie monitoring: they acquire data almost exclusively in the visible and near infrared wavelengths, and do not have the shortwave infrared, mid-infrared and thermal infrared spectral bands required for mapping active fires and burned areas and for their characterization.

Conversely, coarse resolution systems do not have the spatial resolution required for sub-hectare mapping (as an example, a single nadir pixel from MODIS covers 6.25 to 100 ha depending on the band), but their daily temporal resolution and multispectral capabilities have allowed in recent years the development of several fire-related global, multiannual products. These products might not immediately satisfy the requirements for compiling detailed emission inventories, but they are a valuable source of information particularly for large areas and can be integrated with higher resolution data to produce burned area maps at the desired resolution. Section 2.6.3.4 describes possible strategies for the combined use of moderate resolution products and high resolution imagery.

2.6.4.2 Available fire related products

The last few years have seen a considerable effort in the production of systematic, global or continental scale fire monitoring products, and in the coordination between the institutions which have been developing those[70]. Table 2.6.1 reports some of the most commonly used of those products, which are derived from coarse resolution systems. Some discontinued products are reported in Table 2.6.2. At country level (e.g. USA, Portugal) there are systematic post-fire assessment system based on higher resolution satellite data (Landsat); at the moment, however, no systematic, high resolution burned area dataset is available at continental scale - or *a fortiori* at global scale.

Fire monitoring products are derived from data acquired by satellites either in polar or geostationary orbit. Polar-orbiting satellites have the advantage of global coverage and typically higher spatial resolution (currently 250 m - 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 VIIRS (Visible Infrared Imaging Radiometer Suite) on the Suomi National Polar-orbiting Partnership satellite has been providing fire observations since early 2012, which form the basis of a continuing active fire data record (Csiszar et al., 2014; Schroeder et al., 2014). The heritage AVHRR and ATSR sensors were not designed for active fire monitoring and therefore provide less accurate detection; nonetheless, the World Fire Atlas[71], based on nighttime ATSR data, is the longest consistent active fire record currently available, with global data from 1995 to the present day. MODIS, VIIRS as well as the upcoming European Sentinel 3 SLSTR (Sea and Land Surface Temperature Radiometer), 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, sampling the diurnal

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[70] Arino O, et al. (2001), Burn Scar mapping Methods, in 'Global and Regional Vegetation Fire Monitoring from Space' (eds. Ahern F, Goldammer JG, Justice C), pages 105-124.

[71] Arino, O., Casadio, S., Serpe D.,(2012). Global night-time fire season timing and fire count trends using the ATSR instrument series. Remote Sensing of Environment, vol. 116 (pp. 226 - 238).

cycle of fire activity. During its long mission the VIIRS (Visible and Infrared Scanner) on the sun-asynchronous TRMM (Tropical Rainfall Measuring Mission) satellite covered the entire diurnal cycle but with a longer revisiting time.

Geostationary satellites allow for active fire monitoring at a higher temporal frequency (15-30 minutes) on a hemispheric basis, but boreal regions cannot be covered, and the spatial resolution is typically coarser (approx 2-4 km). Regional 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). In addition to SEVIRI, the imagers on the new generation of operational geostationary satellites typically include bands with improved fire detection capabilities (e.g. Advanced Himawari Imager:AHI; GOES-R Advanced Baseline Imager: ABI). A major international effort is being undertaken by GOFC-GOLD to develop a global system of geostationary fire monitoring that will combine data from a number of additional operational sensors to provide near-global coverage.

Several global burned area products exist for specific years and a number of multi-year burned area products have been released (MODIS, L3JRC, GLOBCARBON, CCI) based on coarse resolution satellite data. The only long term (1997 onwards) 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 resolution of the models. The improved along-scan sampling characteristics of VIIRS to reduce pixel size growth provide a potential for the continuation of coarse-resolution burned area mapping at high quality.

The potential research, policy and management applications of satellite products place a high priority on providing statements about their accuracy (Morisette et al. 2006), and this applies to fire related products, if used in the REDD+ context. Inter-comparison of products made with different satellite data and/or algorithms provides an indication of gross differences and possibly insights into the reasons for the differences. However product comparison with independent reference data is needed to determine accuracy[72]. While all the main active fire and burned area products have been partially validated with independent data, systematic, global scale, multiannual validation and systematic reporting has yet to be achieved.

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[72] Justice CO et al. (2000) Developments in the 'validation' of satellite sensor products for the study of land surface. International Journal of Remote Sensing, 21:3383-3390.

Table 2.6.1. List of current operational and systematic continental and global active fire and burned area monitoring systems, derived from satellite data.

Product	Information and data access	Temporal Coverage
MODIS global active fire product (MCD14) and burned areas product (MCD45, MCD64) (University of Maryland / South Dakota State University / University of Idaho / NASA)	http://modis-fire.umd.edu	2000-present
VIIRS active fires (University of Maryland / NOAA / NASA)	http://viirsfire.geog.umd.edu	2012-present
FIRMS: Fire Information for Resource Management System (University of Maryland /NASA)	http://lance-modis.eosdis.nasa.gov	2000-present
Global Fire Emissions Database (GFED3) - multi-year burned area and emissions (NASA)	http://www.globalfiredata.org	1996-present
Meteosat Second Generation SEVIRI fire monitoring (EUMETSAT)	http://landsaf.meteo.pt/	2004-present
Experimental Wildfire Automated Biomass Burning Algorithm: GOES WF-ABBA (University of Wisconsin-Madison / NOAA)	http://cimss.ssec.wisc.edu/goes/burn/wfabba.html	2000-present
Wide Area Monitoring Information System (*WAMIS*) portal –Advanced Fire information System (CSIR, Meraka Institute South Africa)	http://www.wamis.co.za/	2004-present
MACC-II (Monitoring Atmospheric Composition and Climate - Interim Implementation). Global fire analyses and estimates of emissions from fires..	http://www.gmes-atmosphere.eu/about/	2003-present
Fire CCI (ESA. University of Alcala)	http://www.esa-fire-cci.org	Product under development: currently 2006-2008

Table 2.6.2. List of historical systematic continental and global active fire and burned area monitoring systems, derived from satellite data.

Satellite-based fire monitoring	Information and data access	Temporal Coverage
Global burnt areas L3JRC (EC Joint Research Center)	http://bioval.jrc.ec.europa.eu/products/burnt_areas_L3JRC/GlobalBurntAreas2000-2007.php	2000-2007
Globcarbon products (ESA)	http://www.fao.org/gtos/tcopjs4.html	1997-2003
World Fire Atlas (ESA)	http://due.esrin.esa.int/wfa/	1997-2012
TRMM VIRS fire product (NASA)	ftp://disc2.nascom.nasa.gov/data/TRMM/VIRS_Fire/data/	1998-2005

2.6.4.3 Active fire versus burned area products

Active fire products provide the location of all fires actively burning at the overpass time. The short persistence of the signal of active fires means that active fires products are very sensitive to the daily dynamics of biomass burning, and that in situations where the fire front moves quickly, there will be an under-sampling of fire dynamics. Based on the physical characteristics of the sensor, on the characteristics of the fire and on the algorithm used for the detection, a minimum fire size is required to trigger detection. This size is orders of magnitude smaller than the pixel size: as an example, for the MODIS active fire product (Giglio et al, 2003) fires covering around 100m^2 within the 1km^2 nominal pixel have a 90% probability of detection in temperate deciduous forest.

Conversely, burned area products exploit the change of spectral signature induced by the fire on vegetation, which - unlike the signal of actively burning fires - is persistent for a period ranging from weeks (in savannas and grasslands) to years (in boreal forests). Burned area products generally require that a significant portion of the pixel (in the order of half of the pixel) is burned to lead to detection. In some cases this causes a significant underestimation by burned area products, especially in forests, where fires due to clearings and deforestation are smaller than the pixel size of coarse resolution systems. In many of these cases, fires resulting in burned areas too small for detection are large enough to be detected by active fire products. In all cases, users should not use active fire detections directly in area calculations without proper calibration, because the area affected by the fire can be significantly smaller than the pixel size.

The systematic comparison of Active Fires and Burned Area products[73] shows that, depending on the type of environment, the ratio between the number of active fire detections and burned area detections changes significantly, with more burned area detections in grasslands, savannas and open woodlands, and more active fire detections than burned area detections in closed forest ecosystems.

For their physical nature, surface fires generally cannot be detected by burned area algorithms, unless the crown density is very low. If the crown of the trees is not affected, in closed forest the change in reflectance as detected by the satellite is not large enough to be detected. Active fire detection algorithms rely instead on the thermal

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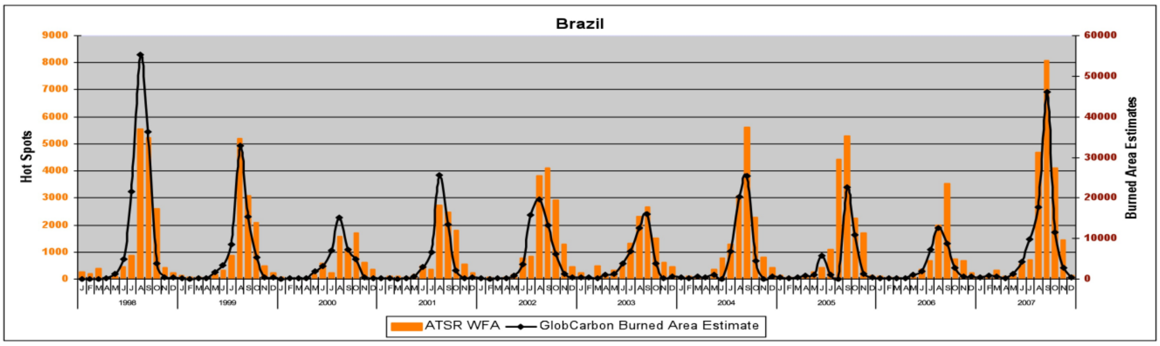
[73] Tansey KJ et al. (2008) Relationship between MODIS fire hot spot count and burned area in a degraded tropical forest swamp forest in Central Kalimantan, Indonesia, *Journal of Geophysical Research,* 113:D23112

signal due to the energy released by the fire and can more often detect surface fires; however, obscuration by non-burning tree canopy still remains an issue.

Figure 2.6.1. Temporal comparison between ATSR World Fire Atlas nighttime active fire counts and Globcarbon[74] burned area estimate in km². While the two products display the same temporal pattern, the areal extent is different by almost an order of magnitude, highlighting the under-sampling issues of active fire products.



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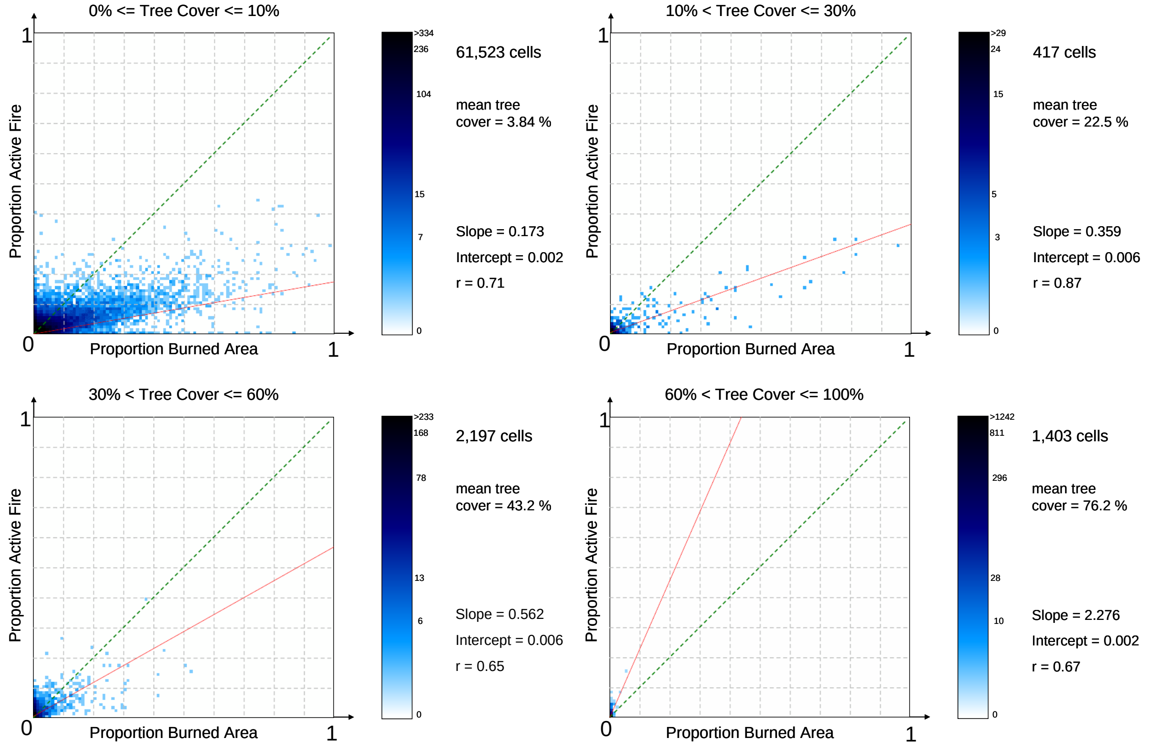
[74] Plummer, S., Olivier, A. (2010), The GLOBCARBON Initiative: Final Results, Proceedings of the living planet Symposium.

Figure 2.6.2. Scatter plots of the monthly proportions of 40x40km cells labeled as burned by the 1km active fire detections plotted against the proportion labeled as burned by the 500m burned area product, for four tree cover class ranges, globally, period July 2001 to June 2002. Only cells with at least 90% of their area meeting these tree cover range criteria and containing some proportion burned in either the active fire or the monthly burned area products are plotted. The Theil-Sen regression line is plotted in red; the white-blue logarithmic color scale illustrates the frequency of cells having the same specific x and y axis proportion values (Source: Roy et al, 2008).



Standard active fire products are generally available within 24 hours of satellite overpass. Some satellite-based fire monitoring systems, including those 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 available within two hours of acquisition[75]. 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.

Burned area products are instead available with days or weeks after the fire event, because the detection is generally performed using a time series of pre-fire and post-fire data.

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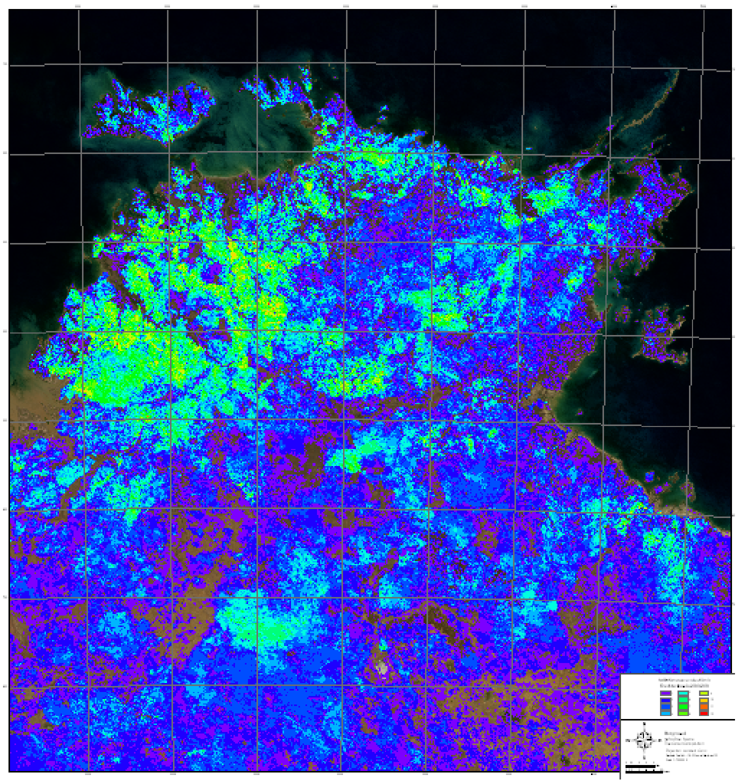
[75] Davies DK et al. (2009). Fire Information for Resource Management System: Archiving and Distributing MODIS Active Fire Data. *IEEE Transactions Geoscience & Remote Sensing* 47:72-79.

2.6.5 Using existing products

Fire is often associated with forest cover change (deforestation, forest degradation) either through deliberate human fire use or wildfire events. As has been described above, satellite data can be used to detect forest fires and map the resulting burned area.

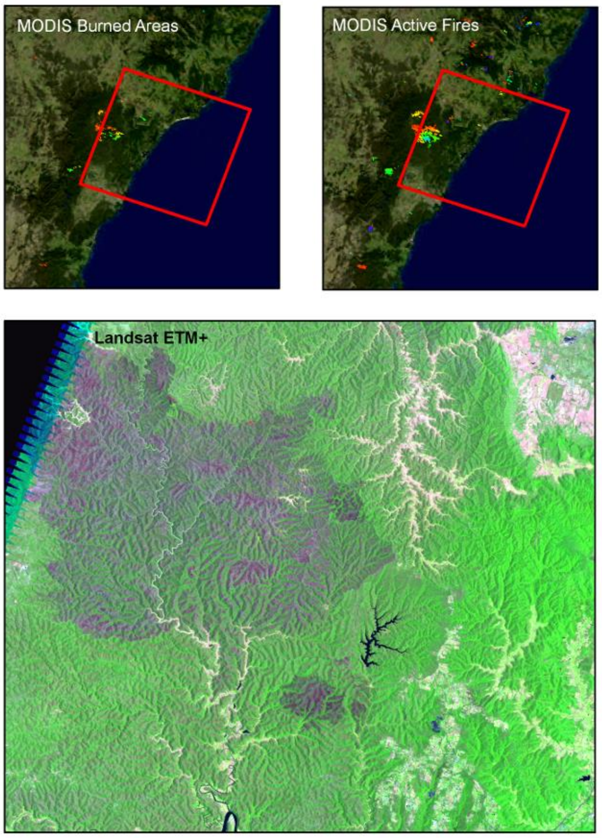
The coarse resolution products of Table 2.6.1 provide a systematic coverage for the past 10 to 15 years, and are specifically designed for sub-continental to global fire monitoring. Hence, if they are directly suitable for studying the fire regime in the fire – prone ecosystems with more than 10% tree cover which could be considered as forest, depending on the definition adopted. Figure 2.6.3 shows an example of fire frequency derived for Northern Australia from 9 years of MODIS burned area data.

Figure 2.6.3. Fire frequency for Northern Australia, derived from MODIS burned area data. The color indicates the number of times a pixel was detected as burned in the 2000-2009 period, from 1 (purple) to 12 (red) using a rainbow colour scale.



Both the information on fire frequency and on the fire seasonality can be effectively retrieved from the existing active fire and burned area product. This information is essential for assessing the emissions due to a particular fire regime: as shown by Korontzi et al. (2004), the emission coefficients of equation 2.6.1 change throughout the season, as a function of the fuel conditions. Fire management programs can lead to decreases in the total area burnt, typically through a combination of prescribed burning, fire prevention and -to a lesser extent- fire suppression. If there is also a shift in the seasonality of fire, the emission coefficients will also change. If a reduction in area burned is accompanied by an increase of the emission coefficients, the net result on emissions might be negative or positive depending on the relative variation of the two terms. The seasonal variation of emission coefficients hasn't been studied systematically for all the fire prone ecosystems: the potential for implementing REDD+ programs based on fire management makes this study a research priority for the next years. The 10 to 15 years historical time series available from remote sensing can be used for as a baseline for the pre-management emissions, while the real-time data could be used to characterize the effectiveness of the fire management interventions.

Figure 2.6.4. Large fire in an open Eucalyptus forest in South East Australia, October 2002. The ground fire is only partially detected by the coarse/moderate resolution MODIS products (top row). On the basis of the information given by such products it is possible to select the time and location for higher resolution imagery (Landsat ETM+ data, bottom row) that allows mapping burned area with c. 0.1 ha spatial resolution.



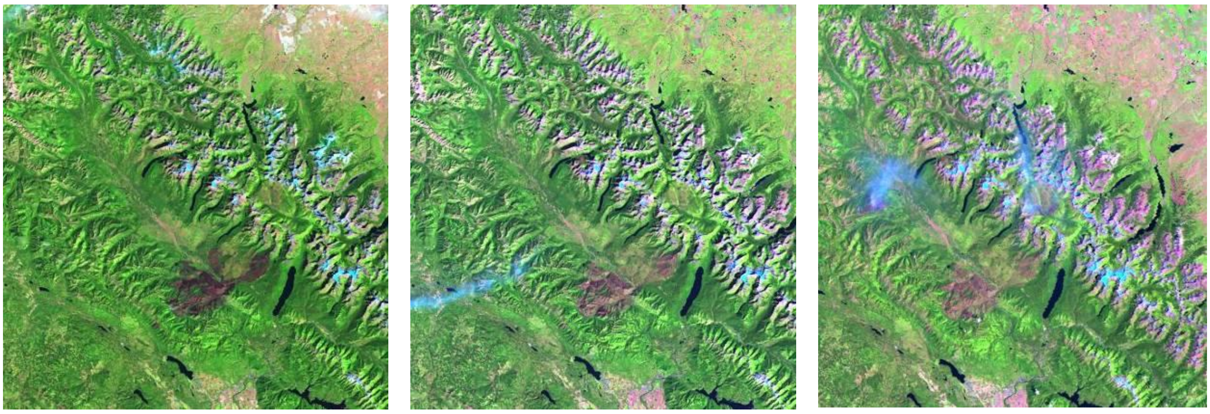
For local scale applications the computation of the total emissions using the indirect approach of Equation 2.6.1 requires burned area maps at a spatial resolution which is not currently provided by any of the automatic systems of Table 2.6.1. Furthermore, the areas burned must be characterized in terms of fire behavior (surface fires, crown fires) and in terms of land use change (fires in forest remaining forest, fires related to deforestation). This information is also not routinely available as ancillary information of the systematic global and continental products.

On the other hand, systems of the Landsat class - or higher resolution - do provide the required spatial resolution, but there are currently no systematic products using those data openly available at global or continental scale. A few countries (USA, Portugal) have implemented Landsat-based burned area assessment systems, but the establishment of similar systems still poses technical challenges and requires considerable investments, because of issues related to data availability (satellite overpass, cloudiness, receiving stations) and computational requirements.

A promising avenue for producing burned area information with the required characteristics for GHG emission computation in a cost-effective way could be the integrated use of high resolution imagery and coarse resolution systematic products. The opening of the Landsat archive free of charge, and the expanding network of receiving stations of free data like CBERS make it possible to use extensively high resolution data for refining the coarse resolution fire information available, also free of charge, as part of the systematic products. The coarse resolution products can be used for the systematic monitoring of fire activity at national scale: when active fires and burned areas are detected in areas of potential interest for deforestation or for forest degradation, they could be complemented by acquiring moderate and high resolution imagery covering the spatial extent and the exact time period of the burning. Through visual interpretation (or using another appropriate automatic or semi-automatic classification technique) of the moderate and high resolution data, and using the coarse resolution products as ancillary datasets, it is possible to produce in a timely and cost effective manner the high resolution burned area maps required by Equation 2.6.1. (Figure 2.6.4).

Satellite data can also be used for post fire assessment: the carbon balance after a fire event depends on whether there is forest regrowth, or conversion to other use (2.1.3). Monitoring with higher resolution imagery over time the location of fire detections, allows understanding if the fire led to land cover change (forest degradation, stand replacement) and if land use change occurred after the fire (e.g. conversion to agriculture). Figure 2.6.5 shows the case of a large fire in Montana (USA) where Landsat images acquired one, two and three years after the fire can be used to rule out any change of land use following the fire.

Figure 2.6.5. Multi-temporal Landsat TM/ETM+ imagery of a forest fire in Western Montana, USA. The first image (left) is acquired shortly after the fire, and the other two at one year intervals. The inspection of multi-temporal imagery after the fire allows monitoring whether land cover and land use changes occur after the fire.



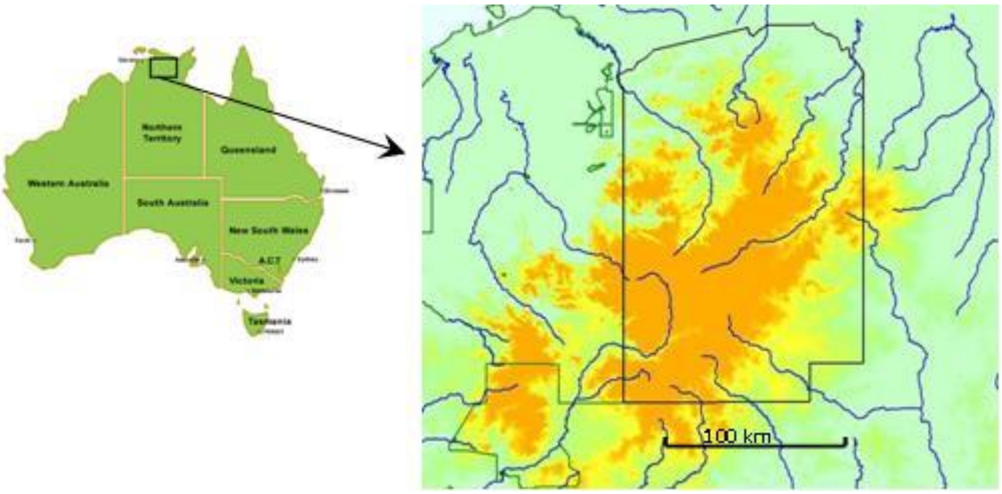
Year 2001 **Year 2002** **Year 2003**

2.6.6 Case study

2.6.6.1 Emission reduction through fire management: the WALFA project (Northern Australia)

The West Arnhem Land Fire Abatement project (WALFA) is an emissions reduction project involving an area of approximately 28,000 km^2 in Western Arnhem Land (Figure 2.6.8). Fire is an important disturbance factor affecting Australian savanna dynamics: it is an extremely fire-prone ecosystem, where frequent low intensity fires burn the grassy understory but rarely inflict tree mortality. Until the early twentieth century the aboriginal population used fire systematically as a way to manage the landscape, but when they were forced off their land after World War II these practices were largely abandoned. As a result, the seasonality of fire has shifted to more frequent, severe, and extensive late-season fires, with negative effects on savanna structure, woody population dynamics, long-term carbon biosequestration and ecosystem degradation.

Figure 2.6.8. Location of the area covered by the WALFA project[76] The Arnhem Land Plateau (in yellow and orange) rises from the savanna lowlands (in green).



Late season fires lead also to increased emissions, because of higher total area burned (early season fires area are patchy and fragmented, late season fires are less so) and to higher combustion completeness. Since 2004, the WALFA project has reintroduced an early-season fire regime that, besides the ecological advantages, measurably reduces atmospheric emissions. This reduction offsets part of the industrial emissions of private companies, which provide funds to cover the cost of the fire management practices introduced in the context of WALFA. Important project-scale methodological enhancements to Equations 2.6.1 and 2.6.2 include explicit incorporation of terms for seasonality (e.g. leaf litter fuels increase under late season conditions; differential effects on fire patchiness and combustion completeness) and fire severity (Russell-Smith et al. 2013). Recent research (Meyer et al., 2012) has established also that, for typical Australian savanna fuel conditions, emission factors for the Kyoto-accountable greenhouse gases CH_4 and N_2O are equivalent under peak early- and late-season burning scenarios.

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[76] image from http://www.savanna.org.au/all/walfa.html

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2.7 ESTIMATION OF UNCERTAINTIES

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2.7.1 Scope of section

Uncertainty is an unavoidable attribute of practically any type of data including area and carbon stock estimates in the REDD+ context. Identification of the sources and quantification of the magnitude of uncertainty will help to better understand the contribution of each source to the overall accuracy and precision of the REDD+ estimates, and to prioritize efforts for their further development.

The proper manner of dealing with uncertainty is fundamental in the IPCC and UNFCCC contexts: The IPCC defines inventories consistent with good practice as those which contain neither over- nor underestimates so far as can be judged, and in which uncertainties are reduced as far as practicable.

In the accounting context, information on uncertainty can be used to develop conservative REDD+ estimates[77]. This principle has been included in the REDD+ negotiating text which emphasizes the need "to deal with uncertainties in estimates aiming to ensure that reductions in emissions or increases in removals are not over-estimated[78].

Building on the IPCC Guidance, this section aims to provide some basic principles for correct estimation of uncertainties. After a brief explanation of general concepts (Section 2.7.2), some key aspects linked to the estimation of uncertainties are illustrated for both area and carbon stocks (Section 2.7.3). The section concludes with the methods available for combining uncertainties (Section 2.7.4) and with the standard reporting and documentation requirements (Section 2.7.5).

2.7.2 General concepts

The most important concepts needed for estimation of uncertainties are explained below.

Bias is an effect that systematically distorts a statistical estimate and deprives it of representativeness or accuracy; bias can occur because of factors such as measurement errors, non-representative sampling methods, or use of an inappropriate emission factor. An estimator in the form of a statistical formula for calculating an estimate is unbiased if its expected value over all possible samples is the true value. In a rigorous sense, unbiasedness and biasedness are properties of estimators, not estimates. Further, just because an estimator is unbiased does not mean that an estimate obtained using the estimator with a particular sample does not deviate substantially from the true value.

Accuracy is the agreement between estimates and exact or true values.

Random error describes the random variation above or below a mean value, and is inversely proportional to precision. Random error cannot be fully avoided, but its adverse effects on a sample-based estimate can be reduced by increasing the sample size.

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[77] See Section 4.4 How to deal with uncertainties: the conservativeness approach

[78] FCCC/SBSTA/2008/L.12

Precision is the level of agreement among repeated measurements of the same quantity or estimates of the same parameter from repeated samples. Precision is inversely proportional to random error.

Uncertainty is a property of a parameter estimate and reflects the degree of lack of knowledge of the true parameter value because of factors such as bias, random error, quality and quantity of data, state of knowledge of the analyst, and knowledge of underlying processes. Uncertainty can be expressed as a percentage confidence interval relative to the mean value. For example, if the area of forest land converted to cropland (mean value) is 100 ha, with a 95% confidence interval ranging from 90 to 110 ha, we can say that the uncertainty in the area estimate is ±10%.

Confidence interval is a range that encloses the true value of an unknown parameter with a specified confidence (probability). In the context of estimation of emissions and removals under the UNFCCC, a 95% confidence interval is normally used. The 95 percent confidence interval is enclosed by the 2.5th and 97.5th percentiles of the probability density function. The meaning of a 95% confidence interval is that 95% of confidence intervals constructed using the same estimators and sampling design, albeit with different samples, will include the true value.

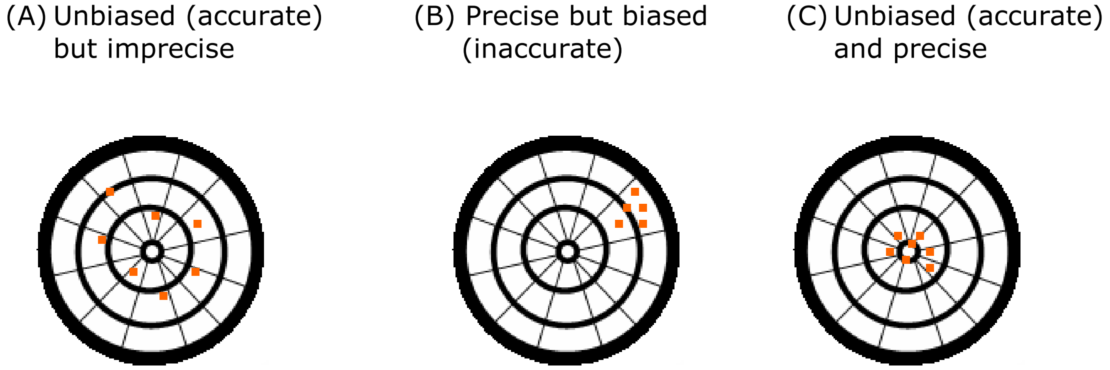
Correlation means the interdependence among both quantitative and qualitative data. It can be described with the Pearson correlation coefficient which assumes values between [-1, +1]. A correlation coefficient of +1 presents a perfect positive correlation, which can occur for example when the same emission factor is used for different years. In case the variables are independent, the correlation coefficient is 0.

Trend describes the change of emissions or removals, and their estimates, over time. In the REDD+ context, the trend will likely be more important that the absolute values.

Trend uncertainty describes the uncertainty in the estimates of change in emissions or removals (i.e. trend). Trend uncertainty is sensitive to the correlation between estimates of parameters used to estimate emissions or removals in the two years. Trend uncertainty is expressed as percentage points. For example, if the trend is +5% and the 95% confidence interval of the trend is +3 to +7%, we can say that trend uncertainty is ±2% points.

The above mentioned concepts of bias, accuracy, random error and precision can be illustrated by analogy with a bull’s eye on a target. In this analogy, each dart represents an estimate obtained with a particular sample. How tightly the darts are grouped represents the precision, and how close they are to the center represents lack of bias or bias (accuracy). Below in Figure 2.7.1 (A), the estimates are close to the center indicating that the estimator is unbiased (accurate), but they are widely spaced and therefore the estimator is imprecise. In (B), the estimates are closely grouped and therefore the estimator is precise (lacking random error), but they are far from the center and so the estimator is biased (inaccurate). Finally, in (C), the estimates are close to the center and tightly grouped, so that the estimator is both unbiased (accurate) and precise.

Figure 2.7.1. Illustration of the concepts of bias (accuracy) and precision.



2.7.3 Quantification of uncertainties

The first step in an uncertainty analysis is to identify the potential sources of uncertainty. Many sources are possible including measurement errors due to human errors or errors in calibration; modelling errors due to inability of the model to fully describe the phenomenon, measurement errors in the predictor variables, parameter uncertainty, and residual uncertainty; erroneous definitions or classifications that lead to double-counting or non-counting; unrepresentative samples; and variability resulting from the use of samples rather than censuses.

2.7.3.1 Uncertainties in area estimates

One estimate of activity data (i.e. area of a land category change) is simply the area indicated by a remote sensing-based map. Although this approach is common, it fails to acknowledge that such maps are subject to classification errors that induce bias into map-based estimators. Many of the factors that contribute to errors in remote sensing-based maps 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 map classification errors and allows for improved area estimates. Most image classification methods have parameters that can be tuned to reduce uncertainties. A good tuning reduces bias, but has a certain degree of subjectivity. Assessing the margin for subjectivity is a necessary task.

An accuracy assessment using a probability sample of greater quality reference data than the map classification should be an integral part of any national monitoring and accounting system. Simple random, systematic, and stratified sampling designs incorporate probability features that facilitate use of calibration estimators that produce more accurate estimates than map-based estimates and more precise estimates than the original survey. Chapter 5 of IPCC Good Practice Guidance 2003 and GFOI (2013) provide recommendations and emphasize that uncertainties should be quantified and reduced as far as practicable.

When using remotely sensed data to estimate land change activity data, the accuracy assessment should lead to a quantitative description of the uncertainty of estimates of area and change in area for land categories. Such analyses may entail category specific thematic accuracy measures, adjustment of map-based area estimates to accommodate known and quantified errors and uncertainties, and construction of best estimate confidence intervals for the area estimates. Statistically robust and quantitative assessments 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.

2.7.3.1.1 Sources of uncertainty

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),
- ☐ location and geo-registration errors for different data sources,
- ☐ 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 kind, amount, and 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 sources of uncertainty 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 minimal mapping units (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 providers (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 (i.e. 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 and confidence intervals for estimates of activity data.

2.7.3.1.2 Accuracy assessment, area estimation of land cover change

Community consensus methods exist for assessing the accuracy of remote sensing-based (single-date) land cover maps. The techniques include assessing the accuracy of a map using 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 using reference data from a probability sample.

Although the same basic methods used for accuracy assessment of land cover maps and estimates can often be used for land cover change, there are additional considerations. First, it is usually more difficult to obtain suitable, multi-temporal reference data of greater quality to use as the basis of the accuracy assessment, particularly for historical times frames. Second, it is easier to assess land cover change errors of commission by examining areas that are predicted as having changed. Because the change classes are often small proportions of landscapes and often concentrated in limited geographic areas, it is more difficult to assess errors of omission within the large area identified as unchanged. If some activity areas are small, stratified random sampling designs rather than simple random or systematic sampling designs, are preferable. Third, 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. These problems are known and have been addressed in studies successfully demonstrating accuracy assessments for land cover change (Lowell, 2001, Stehman et al., 2003).

Two general approaches to constructing remote sensing-based change maps are relevant: direct classification entails construction of the map directly from a set of change training data and two or more sets of remotely sensed data, whereas post-classification entails construction of the map by comparing two separate land cover maps, each constructed using single sets of land cover training data and remotely sensed data. Direct classification is often preferred for multiple reasons including that only a single set of errors must be accommodated (Fuller et al. 2003), although errors for change maps are typically more frequent than for land cover maps. In addition, post-classification may be the only alternative because of factors such as the inability to observe the same locations on multiple occasions as is required to obtain change training data, insufficient numbers of change training observations even when observing the same locations, or a requirement to use an historical baseline map. The accuracy assessment reference data should be distinguished from the training data, although they are often used for both purposes. Of crucial importance, if estimates of accuracy, land cover, or change are to be representative of entire areas of interest, the reference data must be acquire using a probability sampling design, regardless of the manner in which the training data are acquired. Further, the nature of the reference data depends on the method used to construct the map. For maps constructed using direct classification, the reference data must consist of observations of change based for two dates for the same sample locations. For maps constructed using post-classification, reference data may consist of either the same reference data as for maps constructed using direct classification or for two dates, each at different locations.

2.7.3.1.3 Implementation elements for a robust accuracy assessment

For robust accuracy assessment of land cover or land cover change maps and estimates, statistically rigorous validations include three components: sampling design, response design, and analysis design (Stehman and Czaplewski, 1998). 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 either simple random, systematic, or stratified sampling with cluster sampling (depending on the spatial correlation and the cost of the observations). Estimators should be used that follow the principle of consistent estimation, and the sampling strategy should produce accuracy, area, and area change estimates with adequate precision. The sampling design protocol includes specification of the sample size, sample locations and the reference assessment units (i.e. pixels or image blocks). Stratified sampling should be used when some classes are rare which is often the case 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 generally more efficient than simple random sampling and is also more traceable. Sampling variability can be quantified with standard unbiased estimators in the form of statistical formulas. Although unbiased variance estimators for systematic sampling are not available, use of simple random sampling estimators produces conservative variance approximations in the sense that they are slightly greater than the actual variances. Non-sampling or "measurement" errors 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 classes and the definition of agreement for comparing the map classes to the reference classes. Reference information should come from data of greater quality than the map labels. Ground observations are generally considered the standard, although finer resolution remotely sensed data are also used (Stehman, 2009; Sannier et al., 2014). Consistency and compatibility in thematic definitions and interpretation are required to compare reference and map data.

Analysis design

The analysis design includes estimators (statistical formulas) and analysis procedures for accuracy estimation and reporting. Of importance, the estimators must be consistent with the sampling design; for example, simple random sampling estimators cannot be used with accuracy assessment reference data acquired using a stratified sampling design with different within-strata sampling intensities. Comparisons of map and reference data produce a suite of statistical estimates including error matrices, class specific accuracies (of commission and omission error), area and area change estimates, and associated variances and confidence intervals.

2.7.3.1.4 Use of accuracy assessment results for area estimation

As indicated above, all maps based on remotely sensed data include classification errors, and the role of the accuracy assessment is 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. Differences in these two errors may be used 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 map classes. Because areas of land cover change are important drivers of emissions, providing the best possible estimates of these areas is critical.

Multiple statistical procedures for estimating accuracies, activity data and emissions factors, and confidence intervals have been reported (McRoberts et al., 2010). Often, the differences among the estimates they produce are not substantial. Card (1982) provides a relatively simple yet robust approach that is viable when the accuracy assessment sample design is either simple random or stratified random. It is relatively easy to use and provides the estimators 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. Van Oort (2007) describes a method for computing an upper bound for change accuracy from the accuracies of single date maps but without assuming independence of errors at the two dates. McRoberts and Walters (2012) and Olofsson et al. (2013) illustrate methods for constructing confidence intervals for area estimates using information in error matrices. When change reference data have been acquired using a probability sample, the same methods for estimating change and constructing confidence intervals can be used as are used for land cover estimates (Sannier et al., 2014). When reference data for two dates for different locations are used to estimate change for maps constructed using post-classification, methods described and illustrated by McRoberts & Walters (2012), McRoberts (2014), and Olofsson et al. (2014) can be used.

2.7.3.1.5Considerations 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 must 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 system, the verification efforts should help to build confidence in the approach. Greater 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 cover and land-cover change area estimates. Monitoring should work backwards from a most recent reference point to use the greatest 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 (i.e., reinterpretation of small samples in an independent manner by regional experts) should allow some estimation of the quality of the map-based estimates of land cover change. 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 probability sample design can still be useful in understanding the basic uncertainty structure of the map and helping 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 random subset of a probability sample of training observations from the classification process and then using those observations as reference data. 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 to avoid producing a benefit for the country such as overestimation of removals, enhancements and underestimation of emissions reductions.

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 probability sample, using suitable reference data of greater quality, and transparent estimation and reporting of uncertainties. More detailed and agreed technical guidelines for this purpose can be provided by the technical community.

2.7.3.2 Uncertainties in C stocks

Assessing uncertainties in the estimates of C stocks, and consequently of C stock changes (i.e. the emission factors), can be more challenging than estimating uncertainties of the area and area changes (i.e. the activity data). This is particularly true for tropical forests which are often characterized by a high degree of spatial variability and therefore require additional resources to acquire samples that are adequate to produce accurate and precise estimates of the C stocks in a given pool. Furthermore, whereas assessing random and systematic errors separately appears feasible for activity data, it is far more difficult for emissions factors. Here we briefly focus on the main potential sources of systematic errors which are likely the main sources of uncertainty in C stocks at national scales.

There are at least two important— and often unaccounted for —systematic errors that may increase the uncertainty of estimates of emission factors. The first is related to completeness, i.e. which carbon pools are included. In this context, it is important to assess which pool is relevant for the purpose of REDD. To this aim, the concepts of "key categories" and "conservativeness" (e.g. Grassi et al. 2013) could greatly help in deciding which pool is worth assessing and at which level of accuracy. The key category analysis as suggested by the IPCC (see section 2.2.4.1.1) allows identifying which pools in a given country are important. For example, depending on the organic carbon content of soil and the fate of the deforested land (converted to annual croplands or to perennial grasses) the soil may or may not be a important source of GHG emissions (see section 2.3 for further discussion). If the pool is important, higher tier methods (i.e. tier 2 or 3) should be used for estimating emissions, otherwise tier 1 may be sufficient. Furthermore, in some cases, neglecting soil carbon will cause a REDD+ estimate to be incomplete, but still conservative (see section 4.4.1 for further discussion). Although conservativeness is, strictly speaking, an accounting concept, its consideration during the estimation phase may help in allocating resources in a cost-effective way.

The second potential source of systematic error is related to the representativeness of a particular estimate for a carbon pool. For example, the aboveground biomass of forests in deforested areas may be substantially different than mean country or ecosystem nvalues. Accurate estimates of carbon flux require not just mean values over large regions, but biomass estimates for forests actually deforested and logged. However, once again, using sound statistical sampling methods, a country can design a plan to sample the forests undergoing or likely to undergo deforestation and degradation (see section 2.2).

2.7.3.3 Identifying correlations

Correlation means dependency between data or parameter estimates used in calculation as explained in section 2.7.2. Correlation can occur either between estimates for different categories (for example the same emission factor used for different categories) or between estimates for different years (e.g. same emission factor used for different years, or the same estimator with known bias used for area estimate in different years).

No correlation is typically assumed for estimates of activity data between years. For estimates of emission factor, it depends on whether the same estimate of C stock change for the most disaggregated reported level is used across years or not; if different estimates are used, no correlation would be considered; by contrast, if the same estimate is used (i.e. the same carbon stock change for the same type of conversion in different years) a perfect positive correlation would result. The latter case represents the basic assumption given by the IPCC (IPCC 2006) and by most LULUCF uncertainty analyses of Annex I Parties (Monni et al 2007). If the REDD+ mechanism will foresee a comparison between net emissions in different estimates, i.e., between a reference level and net emissions in the assessment period, a high or full correlation of C stock change estimates between periods should be a likely situation for most countries[79].

When uncertainties are estimated for area and carbon stock change, potential correlations must also be identified so that they can be accommodated when combining uncertainties. If Tier 1 method is used for combining uncertainties (i.e. "error propagation", see later), a qualitative judgment is needed whether correlations exist between years and categories. The correlations between years (in both area and carbon stock estimates) can be accommodated using the equations of Tier 1 method. If correlations are identified between categories, it is good practice to aggregate the categories in a manner that correlations become less important (e.g. to sum up all the categories using the same EF before carrying out the uncertainty analysis). If a Tier 2 method is used for combining uncertainties (i.e. "Monte Carlo", see later), the correlations can be explicitly modeled.

2.7.3.4 Combining uncertainties

The uncertainties in individual parameter estimates can be combined using either (1) error propagation (IPCC Tier 1) or (2) Monte Carlo simulation (IPCC Tier 2). In both methods, uncertainties can be combined for the level of estimated emissions or removals (i.e. emissions or removals in a specific year) or trend in estimated emissions or removals (i.e. change of emissions or removals between the two years).

Tier 1 method is based on simple error propagation, and cannot therefore handle all kinds of uncertainty estimates. The key assumptions of Tier 1 method are:

- ☐ estimation of emissions and removals is based on addition, subtraction and multiplication
- ☐ there are no correlations across categories (or if there is, the categories are aggregated in a manner that the correlations become unimportant)
- ☐ none of the parameter estimates has an uncertainty greater than about ±60%
- ☐ uncertainties are symmetric and follow normal distributions
- ☐ relative ranges of uncertainty in the emission factors and area estimates are the same in years 1 and 2

However, even in the case that not all of the conditions are satisfied, the method can be used to obtain approximate results. In the case of asymmetric distributions, the uncertainty bound with the greater absolute value should be used in the calculation.

Tier 2 method, instead, is based on Monte Carlo simulation, which is able to deal with any kind of models, correlations and distribution. However, application of Tier 2 method requires more resources than that of Tier 1.

Tier 1 level assessment

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[79] The basic IPCC assumption of full correlation of emission factors uncertainties between years can be considered likely in the case of emissions from deforestation, primarily because, in many cases, no reliable data on C stock changes of past deforested areas exist in tropical countries. In other words, for each disaggregated reported level (e.g. tropical rain forest converted to cropland), it is likely that the same emission factor will be used both in the historical and in the assessment periods. However, a different situation may occur for forest degradation: in this case, the correlation will ultimately depend on how emissions are calculated, and potential correlations should be carefully examined.

Error propagation is based on two equations: one for multiplication and one for addition and subtraction. Equation to be used in case of multiplication is (Equation 2.7.1):

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

Where:

U_i = percentage uncertainty associated with each of the parameters

U_{total} = the percentage uncertainty in the product of the parameters

Box 2.7.1 shows on example of the use of equation 2.6.1.

Box 2.7.1. Example of the use of Tier 1 method that combines uncertainty in area change and on the carbon stock (multiplication)

	Mean value	**Uncertainty (% of the mean)**
Area change (ha)	**10827**	**8**
Carbon stock (t C/ha)	**148**	**15**

Thus the total carbon stock loss over the stratum is:

10,827 ha* 148 tC/ha = 1,602,396 t C

And the uncertainty = $\sqrt{8^2 + 15^2} = \pm 17\%$

In the case of addition and subtraction, for example when carbon stocks are summed up, the following equation will be applied (Equation 2.7.2):

$$U_{total} = \frac{\sqrt{(U_1 * x_1)^2 + (U_2 * x_2)^2 ... (U_n * x_n)^2}}{|x_1 + x_2 ... + x_n|}$$

Where:

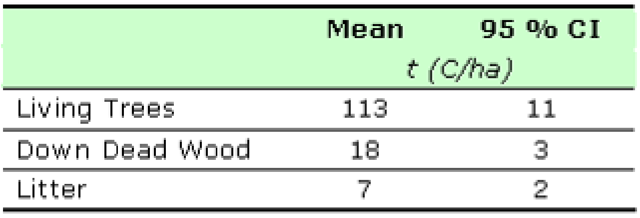
U_i = percentage uncertainty associated with each of the parameters

x_i = the value of the parameter

U_{total} = the percentage uncertainty in the sum of the parameters

An example on the use of Equation 2.7.2 is presented in Box 2.7.2.

Box 2.7.2. Example of the use of Tier 1 method that combines carbon stock estimates (addition)



	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 =

$$\frac{\sqrt{(11\%*113)^2+(3\%*18)^2+(2\%*7)^2}}{|113+18+7|} = \pm 9\%$$

The total uncertainty is ±9% of the mean total C stock of 138 t C/ha

Tier 1 trend assessment

Estimation of trend uncertainty following the IPCC Tier 1 method is based on the use of two sensitivities:

- ☐ Type A sensitivity, which arises from uncertainties that affect estimates of emissions or removals in years 1 and 2 equally (i.e. the variables are correlated across the years)
- ☐ Type B sensitivity which arises from uncertainties that affect estimates of emissions or removals in the year 1 or 2 only (i.e. variables are uncorrelated across the years)

The basic assumption is that estimates of emission factors and other parameters are fully correlated across the years (Type A sensitivity). Activity data, on the other hand, is usually assumed to be uncorrelated across years (Type B sensitivity). However, this association will not always hold and by modifying the calculation, it is possible to apply Type A sensitivities to activity data, and Type B sensitivities to emission factors to reflect particular circumstances. Type A and Type B sensitivities are simplifications introduced for the approximate analysis of correlation. To get more accurate results or to be able to handle correlations explicitly, Tier 2 method would be needed.

Table 2.7.1 can be used to combine level and trend uncertainties using Tier 1 method. The estimates of emissions and removals of each category in the years 1 and 2 are entered into columns C and D, and the respective percentage uncertainties expressed with the 95% confidence interval are entered into columns E and F. For the rest of the columns, the equations are entered as shown in the table. The letters (for example 'C') denote the entries in the same row and respective column, whereas the sums (for example 'ΣC') denote the sum of all the entries in the respective column. The level and trend uncertainties are calculated in the last row of the table.

Table 2.7.1. Tier 1 calculation table (based on IPCC method).

A	B	C	D	E	F	G	H	I	J	K	L	M
Category	Gas	Emissions or removals in year 1	Emissions or removals in year 2	Area uncertainty	Emission factor uncertainty	Combined uncertainty	Contribution to variance by category in year 2	Type A sensitivity	Type B sensitivity	Uncertainty in trend introduced by emission factor uncertainty (Note ii)	Uncertainty in trend introduced by area uncertainty (Note iii)	Uncertainty introduced to the trend in total emissions/
		Mg CO_2	Mg CO_2	%	%	$\sqrt{E^2+F^2}$	$\frac{(G*D)^2}{(\sum D)^2}$	Note i	$\frac{D}{\sum C}$	$I*F$	$J*E*\sqrt{2}$	K^2*L^2
E.g. Forest converted to Cropland	CO_2											
E.g. Forest converted to Grassland	CO_2											
Etc	...											
Total		$\sum C$	$\sum D$				$\sum H$					$\sum M$
					Level uncertainty		$\sqrt{\sum H}$				Trend uncertainty	$\sqrt{\sum M}$

Note i: $\left|100*\frac{0.01*D+\sum D-\left(0.01*C+\sum C\right)}{0.01*C+\sum C}-100*\frac{\sum D-\sum C}{\sum C}\right|$

Note ii: The equation assumes full correlation between the emission factors in the years 1 and 2. If it is assumed that no correlation occurs, the following equation is to be used: $J*F*\sqrt{2}$

Note iii: The equation assumes no correlation between the area estimates in the years 1 and 2. If it is assumed that full correlation occurs, the following equation is to be used: $I*E$

Tier 2 Monte Carlo simulation

The Tier 2 method is a Monte Carlo type of analysis. It is more complicated to apply, but gives more reliable results particularly where uncertainties are large, distributions are non-normal, or correlations exist. Furthermore, Tier 2 method can be applied to models or equations, which are not based only on addition, subtraction and multiplication. See Chapter 5 of IPCC GPG LULUCF for more details on how to implement Tier 2.

Tier 3 Parametric estimation

Total emissions may be estimated as,

$$\hat{E}_{\mathrm{total}} = \sum_{c=1}^{C} \hat{A}_c \cdot \hat{F}_c\,,$$

where c=1,…,C indexes activity classes and $\hat{A}_c$ is the estimate of the area of activity class c and $\hat{F}_c$ is the estimate of the emissions factor for activity class c. The uncertainty of the estimate as expressed by its variance may be estimated as,

$$\mathrm{V\hat{a}r}\left(\hat{E}_{\mathrm{total}}\right) = \mathrm{V\hat{a}r}\left(\sum_{c=1}^{C} \hat{A}_c \cdot \hat{F}_c\right) \approx \sum_{c=1}^{C}\left[\hat{F}_c^2 \cdot \mathrm{V\hat{a}r}\left(\hat{A}_c\right) + \hat{A}_c^2 \cdot \mathrm{V\hat{a}r}\left(\hat{F}_c\right)\right].$$

The estimator is based on a first-order Taylor's series expansion and assumes the estimates of activity areas and emissions factors are all independent and uncorrelated.

2.7.3.5 Reporting and documentation

According to the IPCC, it is good practice to report the uncertainties using a standardized format. For the purpose of this Sourcebook, we present a slightly simplified version of the IPCC table (Table 2.7.2). Columns A to G are the same as in Table 2.7.2 if Tier 1 method is used. Column H will be calculated according to the equation given, whereas the entries in column I will be calculated by category following the same method as in the calculation of the total trend uncertainty. Column J is for additional information on the methods used.

Table 2.7.2. Reporting table for uncertainties.

A	B	C	D	E	F	G	H	I	J
Category	Gas	Emissions or removals in year 1	Emissions or removals in year 2	Area uncertainty	Emission factor uncertainty	Combined uncertainty	Inventory trend for year 2 increase with respect to year 1 (Note a)	Trend uncertainty of the category	Method used to estimate uncertainty (Note b)
		Mg CO_2	Mg CO_2	%	%	%	% of year 1		
E.g. Forest Land converted to Cropland	CO_2								
E.g. Forest Land converted to Grassland	CO_2								
Etc	…								
Total						Level uncertainty		Trend uncertainty	

Note a: $\dfrac{D-C}{C}$

Note b: For example: expert judgment, literature, statistical techniques for sampling, information on the instrument used

2.7.4 Key references for Section 2.7

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2.8 METHODS TO ADDRESS EMERGING ISSUES FOR REDD+ IMPLEMENTATION

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The following sections focus on the remote sensing contributions to emerging issues for REDD+ implementation.

2.8.1 Identifying drivers of deforestation and degradation with remote sensing

Understanding the drivers for deforestation and degradation is necessary to devise effective strategies to reduce emissions. The importance of addressing drivers, and of exchanging information about work in this area, is recognized in decision 15/CP.19 which is part of the Warsaw Framework on REDD+. Distal drivers, i.e., those factors that are the underlying causes such as international markets, trade policies, technological change and population growth, are not readily detectable with remote sensing. Economic and statistical analyses are approaches that can help unravel these distal drivers. Indicators of proximate drivers, i.e., those immediate activities that cause deforestation and degradation, are sometimes possible to detect with remote sensing. For example, large-scale agricultural clearing is readily detectable with accepted methods (see section 2.1). Proximate drivers for degradation are varied and range from local fuel wood collection to wildfires.

Indicators can be used to infer the presence or absence of proximate drivers. Combining the presence or absence of drivers with the presence or absence of deforestation/degradation can suggest which drivers are most influential in particular places. For example, deforestation identified in areas of road expansion suggests (but does not prove) that road expansion is a proximate driver for the deforestation. Drivers may vary in different regions within a country, in which case region-specific strategies to reduce emissions would be most effective. For example, presence of large-scale agricultural clearing would suggest that policies aimed at large-landholders rather than smallholder farmers would be most effective in reducing deforestation in the region where large clearings are identified.

Remote sensing can provide information useful for assessing which drivers are present in particular locations (Table 2.8.1). The size of deforestation clearings is a strong indicator of industrial vs. smallholder agricultural expansion as a deforestation driver. Size can be determined from analysis of deforestation polygons mapped with Landsat-like sensors. Medium resolution data are useful for identifying the presence of new deforestation but cannot be used to accurately determine the clearing size expect where the clearings are very large (>~100 ha). Remote sensing can also provide information on land use following deforestation, for example row crops or pasture. High temporal resolution from MODI has proven useful for this purpose based on the higher NDVI of row crops during the growing season. Distinguishing among row crops or pasture as the land use following deforestation helps assess which commodities are deforestation drivers.

Remote sensing of drivers associated with degradation can suggest which policies might be effective in reducing degradation. The presence of logging roads (see section 2.2) indicates the possibility of unsustainable logging. The presence of burn scars (see section 2.5) indicates wildfire as a possible driver of degradation. Remote sensing is more problematic for indicators of degradation drivers such as local wood collection or forest grazing. High resolution and ground data are required, with no widely accepted methods for mapping these types of degradation.

Scenarios of future deforestation and degradation can be constructed based on understanding of which drivers are important and how they might occur in the future.

Scenario-building must also account for biophysical features that determine where deforestation/degradation occurs. For example, deforestation for industrial agriculture is generally less likely on hill slopes or where precipitation is very high. Careful assessment of the economic, social and biophysical factors associated with deforestation/degradation in the particular national circumstance is needed to construct plausible future scenarios.

Table 2.8.1. Remote sensing of proximate drivers of deforestation and degradation.

Driver	Indicator of driver	Method	Sensors
Deforestation:			
Industrial agricultural clearing for cattle ranching, row crops etc.	Large-clearings (>25 ha); post-clearing land use	Size of deforestation polygons (see section 2.1); map of land use following deforestation	MODIS, Landsat-like sensors
Small-scale agricultural clearing for pastures, shifting cultivation, smallholder farming	Small clearings (<25 ha)	Size of deforestation polygons (see section 2.1)	Landsat-like sensors
Infrastructure expansion (roads, mines etc.)	Road networks, new mines	Visual analysis or automated detection of infrastructure features	Landsat-like and high resolution sensors
Degradation:			
Unsustainable logging	Logging roads	Spectral mixing (see section 2.1.3)	Landsat-like sensors
Fuel wood and NTFP collection	Footpaths, low biomass, ground data	No accepted method	High resolution
Forest grazing	Ground data	No accepted method	High resolution
Wildfire	Burn scars	Burn scar detection (see section 2.5)	Landsat-like sensors, MODIS

2.8.2 Safeguards to ensure protection of biodiversity

Results-based payments for REDD+ activities could possibly require documentation that biodiversity is protected. Species richness and abundance cannot be directly identified with remote sensing. Ground surveys of biodiversity are unlikely to be available in many locations and are not possible to cover all forest area within a country. Habitat quality of forests is an indirect proxy of biodiversity that could provide input for assessing this safeguard. For example, tree plantations generally maintain lower biodiversity than forests. In some cases tree plantations can be distinguished from forest with visual inspection of high resolution data. Evolving technologies such as radar show promise in making this distinction although no standard methods have been widely applied. Remote sensing of forest type (e.g. deciduous, evergreen) based on spectral characteristics or phenological information might provide other indirect measures of habitat quality. Methods for determining forest type include visual and digital classification (see section 2.1) based on ground knowledge of forest types.

2.8.3 Safeguards to ensure rights of forest dwellers

An important aspect of REDD+ implementation is assurance that knowledge and rights of stakeholders have been maintained. Ground-based information on forest dwelling communities, ownership and use rights of forests and other non-remote sensing data are of primary importance for determining the effectiveness of safeguards. Remote sensing could aid this effort by delineating forest extent and changes in forest area within designated indigenous lands.

2.8.4 Monitoring displacement of emissions and permanence at a national scale

Leakage, or displacement of emissions, occurs if emissions increase in one area due to reductions of emissions in another area. Determining leakage at a national scale requires consistent and transparent monitoring of changes in forest area across the entire forest extent within a country's boundaries. For a large country, detailed monitoring across the entire forest extent can be prohibitive. Remote sensing data can assist in identifying "hot spots" of deforestation to focus detailed analysis on those areas while checking whether deforestation has spread to areas outside the hot spots. Active fire monitoring (see section 2.5.4) might indicate locations with new deforestation. In addition, automated or visual analysis of time series of medium resolution (e.g., MODIS) data to identify areas of possible new deforestation would require less data processing than high resolution data over the entire forest extent. The key requirement is that the full national forest extent must be assessed to determine whether leakage has occurred at a national scale.

Remote sensing also has an important role to play in addressing the risks of reversals and verifying that REDD+ actions have a permanent positive impact in the long term. The advantage of consistent time series and the value to build satellite data archives that allow updated and retrospective analysis is a unique characteristic that remote sensing provides as data source.

2.8.5 Linking national and sub-national monitoring

A national monitoring system provides the foundation for reporting and to verify that the sum of all sub-national forest-related or REDD+ activities have a positive effect as regards human impact on forest carbon. Thus, a systematic and continuous national monitoring effort is clearly essential. However any country contemplating a REDD+ program will need to decide where to place its major efforts, based on what policies and programs are considered to be most effective in its own context. Here the main consideration will be not only: what drivers and processes are most active and relevant and can realistically and effectively be tackled at least in an initial phase of implementation.

Thus, a national forest carbon monitoring system should provide data nationally but also be flexible for more detailed, accurate measurement at the subnational scale driven by REDD+ related activities that or often focused on specific areas. This could be through a national stratification system that provides for all (subnational) REDD+ implementation activities to be measured with more precision and accuracy in REDD+ action areas and less detailed, systematic monitoring in the rest. A national stratification system could be based on forest carbon density and types of human activities (and thus REDD+ actions).

Such a system would help to show the effectiveness of subnational activities by accounting for national displacement of emissions and permanence. Remote sensing can play an important role to identify areas of change and systematically track performance and activities over time.

2.9 GUIDANCE ON REPORTING

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2.9.1 Scope of section

2.9.1.1 The importance of reporting good quality information

Under the UNFCCC, information reported in greenhouse gases (GHG) inventories represents an essential link between science and policy, providing the mean by which the COP can monitor progress made by Parties in meeting their commitments and in achieving the Convention's ultimate objective[80]. In any international system in which an accounting procedure is foreseen - as in the Kyoto Protocol, and in the future, in the Paris Agreement – the information reported in a Party's GHG inventory (GHGI) represents the basis for assessing each Party's performance as compared to its commitments/contributions as set according to a reference scenario. Therefore, the GHGI therefore represents the basis for tracking progress in the implementation of mitigation actions, including REDD+ activities, and consequently for assigning eventual incentives (e.g. result-based payments for REDD+).

The quality of GHG inventories relies not only upon the robustness of the science underpinning the methodologies and the associated accuracy 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.

2.9.1.2 Overview of the chapter

Section 4.2 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 4.3 outlines the major challenges that developing country Parties will likely encounter when implementing the reporting principles described in section 4.2.

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[80] UNFCCC - Article 2: The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Section 4.4 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 4.3.

2.9.2 Overview of reporting principles and procedures

2.9.2.1 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 transparent and complete, consistent, accurate and therefore comparable GHG information, the COP has developed specific reporting guidelines that detail reporting requirements. Although reporting guidelines currently differ between developed and developing countries, it is expected that under the Paris Agreement guidelines will be re-arranged in a single set applicable across all Parties, where the preparation of GHG information be based on IPCC methodologies to ensure a transparent, consistent and accurate reporting of GHG emissions and removals by each Party (and therefore a comparable reporting across Parties).

At present, two different sets of reporting guidelines exist for Annex I and non-Annex I Parties. This difference reflects the fact that Annex I (AI) Parties are required to report detailed data, on an annual basis, which are subject to in-depth review by teams of independent experts. Revised non-Annex I Parties (NAI) requirements are as follows.

Non-Annex I Parties reporting

- National Communications (NC), containing information on national circumstances, national GHG emissions/removals[81], steps taken or envisaged to implement the Convention, and any other information considered relevant to the achievement of the objective of the Convention including, if feasible, material relevant to calculations of global emissions and emission trends;
- Biennial Update Reports (BURs), containing updated information on national circumstances and institutional arrangements for reporting on a continuous basis[82], national GHG emissions/removals information[83], including a national inventory report, and information on mitigation actions[84], effects, needs, and support received.

National communications may be submitted (decision 10/CP.2) by non-Annex I Parties every 4[5] years following decisions for each submission taken by the Conference of the Parties (COP). They are prepared and reported periodically by non-Annex I Parties based on agreed reporting guidelines (decision 17/CP.8)[85] based on methodologies

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[81] For the years 1994 (1st NC), and 2000 (2nd NC).

[82] This includes, for REDD+ activities, the national forest monitoring system, including for providing information on how the safeguards are being addressed and respected (decision 1/CP.16)

[83] The decision text has not fixed the starting year nor the time-series of GHG estimates to be reported in the BUR. Anyhow the pace of the time series will be biennial from 2014 onwards.

[84] i.e. Nationally Appropriate Mitigation Actions (NAMAs), REDD+ activities

[85] Guidelines for the preparation of national communications from Parties not included in Annex I to the Convention (decision 17/CP.8) at http://unfccc.int/resource/docs/cop8/07a02.pdf

developed by the IPCC[86] and adopted by the COP. Submissions by non-Annex I can be found here: http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php

Biennial Update Reports are to be submitted (2/CP.17) by non-Annex I Parties every 2 years, and are prepared on the basis of agreed reporting guidelines (decision 2/CP.17)[87] based on methodologies developed by the IPCC[88] and adopted by the COP. Least developed country Parties and small island developing States may submit biennial update reports at their discretion. The first biennial report (BUR1) is due by December 2014 and it is expected to contain information on current levels and trends of GHG emissions and removals within their territories.

The Biennial Update Reports will be subject[89] to a technical assessment[90] as part of the International Consultation and Analysis process, which is aimed at increasing the transparency of mitigation actions and their effects.

Decision 14/CP.19 says that BURs should be used to provide data and information on emissions and removals associated with REDD+ activities and associated reference levels. The decision requests that Parties seeking results-based payments provide (on a voluntary basis) a Technical Annex to the BUR with data and information specified in an Annex to 14/CP19. The decision also covers inclusion LULUCF experts in the BUR assessment process, and sets out what they should assess, including comprehensiveness, transparency, consistency and accuracy of the data information

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[86] Currently for non-Annex I Parties, Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (at http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html) have been adopted and 2000 IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (at http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html) and 2003 IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html) have been encouraged to be used (see Decision 17/CP.8). Note that for the LULUCF (Land Use, Land-Use Change & Forestry) sector methodologies provided in the 2003 GPG for LULUCF replace those provided in the Revised 1996 IPCC Guidelines.

Although, non-Annex I Parties may use the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html) and any further IPCC supplement to these Guidelines as adopted under the UNFCCC.

[87] UNFCCC biennial update reporting guidelines for Parties not included in Annex I to the Convention (Decision 2/CP.17) can be found at http://unfccc.int/resource/docs/2011/cop17/eng/09a01.pdf

[88] Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (at http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html), 2000 IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (at http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html) and 2003 IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html) should be used for reporting (see Annex III to Decision 2/CP.17). For the LULUCF (Land Use, Land-Use Change & Forestry) sector categories provided in the 2003 GPG for LULUCF effectively replace those provided in the Revised 1996 IPCC Guidelines. Presumably non-Annex I Parties who wish to do so may use the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html) and IPCC supplements to these Guidelines as adopted under the UNFCCC, e.g. the 2013 Wetlands supplement available at http://www.ipcc-nggip.iges.or.jp/public/wetlands/index.html .

[89] Decision 2/CP.17 (*Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention*) at http://unfccc.int/resource/docs/2011/cop17/eng/09a01.pdf#page=4

[90] Decision 20/CP.19 (*Composition, modalities and procedures of the team of technical experts under international consultation and analysis*) at

http://unfccc.int/resource/docs/2013/cop19/eng/10a02.pdf provided on reference levels. The decision recognizes that further modalities may be developed in the case that REDD+ actions are eligible for market access.

Annex I Parties reporting

- National Communications (NC), containing information, from the last submitted GHG Inventory, on national GHG emissions/removals, climate-related policies and measures, GHG projections, vulnerability and adaptation to climate change, financial assistance and technology transfer to non-Annex I Parties, and actions to raise public awareness on climate change;
- National GHG Inventories (NGHGI), submitted annually with GHG estimates. A NGHGI submitted in year x comprises the Common Reporting Format (CRF) tables containing time-series of GHG emission estimates from 1990 till the year x-2, plus a National Inventory Report (NIR), with information on background data and methods used, and the data analysis and institutional arrangements.
- Biennial Reports (BRs), which outline progress in achieving net emissions reductions and provision of financial, technological, and capacity-building support to non-Annex I Parties for dealing with climate change. The first BR was submitted by January 2014.

Each report is subject to a review process[91] coordinated by the UNFCCC Secretariat and undertaken by experts from the UNFCCC Roaster of Experts (RoE).

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[91] The review process is ruled by the Annex to Decision 23/CP.19 (*Guidelines for the technical review of information reported under the Convention related to greenhouse gas inventories, biennial reports and national communications by Parties included in Annex I to the Convention*) at http://unfccc.int/resource/docs/2013/cop19/eng/10a02.pdf

The objectives of the review of information reported under the Convention related to GHG inventories, BRs and NCs and pursuant to relevant decisions of the COP are the following:

a. To provide, in a facilitative, non-confrontational, open and transparent manner, a thorough, objective and comprehensive technical review of all aspects of the implementation of the Convention by individual Annex I Parties and Annex I Parties as a whole;
b. To promote the provision of consistent, transparent, comparable, accurate and complete information by Annex I Parties;
c. To assist Annex I Parties in improving their reporting of information contained in GHG inventories, BRs and NCs and pursuant to other relevant decisions of the COP and the implementation of their commitments under the Convention;

Table1. Summary of COP decisions and IPCC Guidelines relevant to UNFCCC reporting by Parties.

Decision/Document	Link	Description
Convention Text (UNFCCC)	http://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf	Commits for Parties to report information on their GHG emissions and removals and on mitigation actions implemented.
3/CP.5 Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part II: UNFCCC reporting guidelines on national communications	http://unfccc.int/resource/docs/cop5/07.pdf	Establishes the structure of the NC; the information to be provided in the NC; the principles and methodologies to be applied to compile information and elaborate estimates.
15/CP.17 Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual greenhouse gas inventories	http://unfccc.int/resource/docs/2011/cop17/eng/09a02.pdf	Establishes the structure of the GHGI; the information to be provided in the GHGI; the principles; and methodologies to be applied to compile information and elaborate estimates.
24/CP.19 Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual greenhouse gas inventories	http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf	From inventories submitted in April 2015, replaces the version provided in Decision 15/CP.17.
2/CP.17 UNFCCC biennial reporting guidelines for developed country Parties	http://unfccc.int/resource/docs/2011/cop17/eng/09a01.pdf	Establishes the information to be provided in the BR (noting that principles and methodologies to be applied to compile information and elaborate estimates are those applied for NC and GHGI).
17/CP.8 Guidelines for the preparation of national communications from Parties not included in Annex I to the Convention	http://unfccc.int/resource/docs/cop8/07a02.pdf	Establishes the structure of the GHGI; the information to be provided in the GHGI; the principles and methodologies to be applied to compile information and elaborate estimates.

2/CP.17 UNFCCC biennial update reporting guidelines for Parties not included in Annex I to the Convention	http://unfccc.int/resource/docs/2011/cop17/eng/09a01.pdf	Establishes the information to be provided in the BUR (noting that principles and methodologies to be applied to compile information and elaborate estimates are those applied for NC and GHGI)
12/CP.17 Guidance on systems for providing information on how safeguards are addressed and respected and modalities relating to forest reference emission levels and forest reference levels as referred to in decision 1/CP.16	http://unfccc.int/resource/docs/2011/cop17/eng/09a02.pdf#page=16	Provides guidance on information to be submitted on how safeguards have been addressed and respected
13/CP.19 Guidelines for submissions of information on reference levels	http://unfccc.int/resource/docs/2013/cop19/eng/10a01.pdf	Provides guidance on information to be submitted on how the reference levels have been constructed
14/CP.19 Modalities for measuring, reporting and verifying	http://unfccc.int/resource/docs/2013/cop19/eng/10a01.pdf	Provides guidance on information to be submitted on how the results of activities have been estimated
2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (KP Supplement) (adopted by decision 6/CMP.9)	http://www.ipcc-nggip.iges.or.jp/public/kpsg/	Provides good practices to be followed, in addition to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, in order to ensure accuracy of estimates of KP-LULUCF activities
2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement) (adopted by decision 23/CP.19)	http://www.ipcc-nggip.iges.or.jp/public/wetlands/index.html	Provides supplementary methods, to those provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, for collecting and compiling information and for preparing GHG estimates for wetlands and drained soils.
2006 IPCC Guidelines for National Greenhouse Gas Inventories (adopted by decision 15/CP.17)	http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html)	Provides methods for collecting and compiling information and for preparing GHG estimates, which are consistent with the reporting principles (transparency, completeness, consistency, accuracy and therefore, comparability). This is the most recent full set of guidelines for national GHG inventories published by IPCC.
2003 IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (adopted by decisions 2/CP.17, 17/CP.8)	http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html	Provides good practices to be followed, in addition to the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, in order to ensure accuracy of LULUCF estimates.
2000 IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (adopted by	http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html	Provides good practices to be followed, in addition to the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, in order to ensure accuracy of

decisions 2/CP.17, 17/CP.8)		estimates.
Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (adopted by decisions 2/CP.17, 17/CP.8)	http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html	Provides methods for collecting and compiling information and for preparing GHG estimates, which are consistent with the reporting principles.

However, the Paris Agreement set for all Parties common obligations for reporting:

- a national GHG inventory report;
- information to track progress made in implementing and achieving the nationally determined contribution;

Further,

- for developed country Parties is required to provide information on financial, technology transfer and capacity-building support provided to developing country Parties
- for developing country Parties is required to provide information on financial, technology transfer and capacity-building support received, if any

Biennial reports will likely be used for such reporting obligations, since they already contain information on national GHGI, mitigation actions and on technology transfer, finance and capacity building. Although the current scope of BURs has to be aligned with that of BRs.

Information reported under the Paris Agreement will be subject to a technical review and to a multilateral consideration of the implementation and achievement of the nationally determined contributions, together with consideration on finance support provided and received and associated technology transfer and capacity building. Also such review process seems similar to that currently applied to biennial reports although it is expected that for both, the ICA and the IAR, it is expected that the scope will be aligned and will include the assessment of transparency and completeness of information provided, as well as the assessment of its consistency across time and across reports and of its accuracy.

2.9.2.2 Inventory and reporting principles

The UNFCCC, establishes five principles to guide the estimation and the reporting of emissions and removals of GHG: Transparency, Consistency Comparability Completeness and Accuracy. These principles have been referred to in previous chapters and are summarized below

Transparency - all the assumptions and the methodologies used in the inventory should be clearly explained and appropriately documented, so that anybody could verify its correctness. GHG estimates are reported at a level of disaggregation which allows to verify underlying calculation and most relevant background data are provided in the report.

Consistency - the same definitions and methodologies should be used over time, to 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 level must be tracked in the future (in the Kyoto language it is said "once in, always in"). Similarly, inclusion of new sources or sinks which were not previously reported (e.g., a carbon pool), should be reported for the reference level and all subsequent years. The consistency 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 organizations (e.g. UNFCCC, FAO). In that case, any discrepancy should be adequately justified.

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).

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 - 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.

These principles help guide the process of independent review/analysis of information submitted to the UNFCCC.

Decision 14/CP.19 (Modalities for measuring, reporting and verifying) establishes that the technical analysis of information on REDD+ activities should check whether information is transparent, consistent, complete and accurate. Completeness refers to the provision of information allows for the reconstruction of the results. Being transparent, complete, consistent and accurate the estimates can be regarded as comparable although this principle is not mentioned in REDD+ decisions.

2.9.2.3 Structure of a GHG inventory

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

Reporting Tables are a set of standardized data tables that contain mainly quantitative (numerical) information. Box 4.2.1 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 subdivisions) according to criteria such as climate zone, management system, soil type, vegetation type, tree species, ecological zones, national land classification or other factors.
- ❑ *Activity data*, i.e., area of land (in thousands of ha) subject to gross deforestation, degradation and management of forests (see Section 2.1).
- ❑ *Emission factors*, i.e., the C stock change per unit of area for each carbon pool (see Sections 2.2 & 2.3). Implied emission factors appear in tables and are back-calculated by dividing estimated emissions by activity data, and serve mainly for comparative purposes.
- ❑ *The total change in C stock*, obtained by multiplying each activity data by the relevant C stock change factor.
- ❑ *The total emissions* (expressed as CO_2equivalent).

Box 4.2.1: 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)							CHANGE IN CARBON STOCK (2)						
			carbon stock change per **unit area** in:							carbon stock change in:						
			biomass		dead organic matter		soils		Implied emission factor per area (3)	Biomass		dead organic matter		soils		Total CO_2 emissions (3)
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.

To help ensure the completeness of an inventory, it is good practice to fill in information for all entries in the CRF tables. If actual emissions and removals quantities have not been estimated or cannot otherwise be reported, inventory compilers 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. This notation key also applies to cases in which net C stock changes are not significant, as allowed for by the Annex to Decision 24/CP.19 (para37), or the C pool is assumed to be at long-term equilibrium.
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,
NA (Not Applicable)	For activities in a given source/sink category that do not result in emissions or removals of a specific gas.
NO (Not Occurring)	An activity or process does not occur within a country.

Reporting tables have a documentation box for use to provide references to relevant sections of the Inventory Report, and any additional information if needed.

In addition to tables like those illustrated in Box 4.2.1, 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 (i.e. the IPCC fourth Assessment Report, contains the following GWPs: 25 for CH_4 and 298 for N_2O).
- Summary tables (with all the gases and all the emissions/removals).
- Tables with emission trends (covering data also from previous inventory year).
- Tables for illustrating the results of the key category analysis, the completeness of the reporting, and any recalculations.

Inventory Report: The NIR contains comprehensive and transparent information about the inventory, including:

- An overview of trends for aggregated GHG emissions/removals, 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.
- 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 and archiving of data.
- A description of the institutional arrangements for inventory planning, preparation and management.

- ☐ Information on planned improvements.

Furthermore, all relevant inventory information should be compiled and archived, including all disaggregated emission factors, activity data together with 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.

2.9.2.4 Reporting for REDD+ activities

COP19 in Warsaw in November 2013 agreed a set of COP decisions[92] establishing the rules and requirements for reporting information on REDD+ activities. In particular, Parties implementing REDD+ activities are expected to report on:

1. The national strategy or action plan.
2. The National Forest Monitoring System (NFMS),
3. Safeguards, including the system to collect information on how safeguards are addressed and respected,
4. The Forest Reference Emissions Level and/or Forest Reference Level (FREL/FRL),
5. GHG emissions and removals during the implementation period of REDD+ activities,

1. The national strategy or action plan

Decision 1/CP.16 and 9/CP.19 set requirements and procedures for preparing, submitting and assessing a national strategy or action plan. In particular:

- A national strategy or action plan is to be developed for the implementation of REDD+ activities (1/CP.16);
- It is expected that the national strategy or action plan address safeguards;
- It is expected that the national strategy or action plan be part of the BUR, as information on NAMAs;
- The national strategy or action plan is published into the REDD+ portal of the UNFCCC (9/CP.19).
- Unless submitted in the BUR, the national strategy or action plan is not subject to the technical analysis.

2. The National Forest Monitoring System (NFMS)

An NFMS is to be established[93] (1/CP.16). Decision 11/CP.19, together with decisions 4/CP.15, 1/CP.16 and 9/CP.19 set requirements and procedures for constructing, submitting and assessing the NFMS. According to national circumstances and capabilities, (4/CP.15 and 11/CP.19) the NFMS:

  - ○ Is built on existing systems, as appropriate;
  - ○ Is based on IPCC guidance and guidelines;
  - ○ Enables the assessment of different types of forest in the country, including natural forest;

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[92] COP decisions are at: http://unfccc.int/documentation/decisions/items/3597.php#beg

    - Uses a combination of remote sensing and ground-based forest carbon inventory approaches for estimating, as appropriate, forest C stocks and forest areas and their changes and associated anthropogenic forest-related GHG emissions and removals;
    - Provides estimates that are transparent, consistent over-time, accurate, and that reduce uncertainties as far as possible, taking into account national capabilities and capacities. It may also provide information on how safeguards are addressed and respected;
    - Is transparent and its results are available and suitable for review as agreed by the COP;
    - Allows for further improvements as per the phased-approach.

In the technical annex to the BUR, as established by decision 14/CP.19, a description of NFMS and of the institutional roles and responsibilities for measuring, reporting and verifying the results is to be included (14/CP.19). Information on NFMS is published into the REDD+ portal of the UNFCCC. Information on NFMS is subject to technical analysis as part of the information included into the technical annex to the BUR (14/CP.19).

3. Safeguards, including the system to collect information on how safeguards are addressed and respected

Decision 12/CP.19, together with decisions 1/CP.16, 12/CP.17 and 9/CP.19 set requirements and procedures for preparing and submitting information on how safeguards are addressed and respected. In particular:

- Safeguards have to be addressed and respected when implementing REDD+ activities (1/CP.16);
- Information safeguards should be included in the NC, and published into the REDD+ portal of the UNFCCC, and be updated periodically;
- According to national circumstances and capabilities, the system for providing information on how safeguards have been addressed and respected (12/CP.17):
    - Is built, at national level, on existing systems, as appropriate;
    - Provides transparent and consistent information that is accessible by all relevant stakeholders and updated on a regular basis;
    - Allows for further improvements as per the phased-approach.
- Information to be provided on safeguards (14/CP.19) is whether:
    - REDD+ actions complement or are consistent with the objectives of national forest programmes and relevant international conventions and agreements;
    - There is in place a transparent and effective national forest governance structures, taking into account national legislation and sovereignty;
    - The knowledge and rights of indigenous peoples and members of local communities are respected;
    - Relevant stakeholders, in particular indigenous peoples and local communities, fully and effectively participate in the REDD+ actions;
    - REDD+ actions are consistent with the conservation of natural forests and biological diversity, ensuring that the actions are not used for the conversion of

natural forests, but are instead used to incentivize the protection and conservation of natural forests; [94]

    - The risk of reversals is addressed[95];
    - The displacement of emissions is reduced[96].
- Unless submitted in the BUR, information on how safeguards have been addressed and respected is not subject to the technical analysis.

4. The Forest Reference Emissions Levels and/or Forest Reference Levels (FREL/FRL)

Decision 13/CP.19, together with decisions 4/CP.15, 1/CP.16, 12/CP.17 and 9/CP.19 set requirements and procedures for constructing, submitting and assessing the FREL/FRL. In particular:

- A FREL/FRL is to be established (1/CP.16);
- A FREL/FRL is based on historical data and adjusted for national circumstances (4/CP.15);
- Information to be provided in the submission of FREL/FRL, and that therefore needs to be considered in its construction, should be guided by the most recent IPCC guidance and guidelines, as adopted or encouraged by the COP. In particular, the submission contains (12/CP.17):
    - Transparent, complete, consistent and accurate information, including historical data and methodological information, used at the time of construction of FREL/FRL, including, inter alia, as appropriate, a description of data sets, approaches, methods, models, if applicable and assumptions used, descriptions of relevant policies and plans, and descriptions of changes from previously submitted information;
    - Pools and gases, and activities which have been included in FREL/FRL and the reasons for omitting a pool and/or activity from the FREL and/or FRL, noting that significant pools and/or activities should not be excluded;
    - The definition of forest used in the construction of FREL/FRL and, if appropriate, in case there is a difference with the definition of forest used in the NGHGI or in reporting to other international organizations, an explanation of why and how the definition used in the construction of FREL/FRL was chosen;

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[94] Be aware that the safeguard is not respected by excluding from REDD+ reporting the conversion of natural ecosystems, including natural forests, into industrial forest plantations; since in many cases, including the conversion of natural forests into industrial forest plantations, such conversion results in accounting for a net emission, whose exclusion from REDD+ accounting would correspond to a displacement of emissions. However, if such conversion results in accounting for a net sequestration of carbon, then such accounted quantities have to be zeroed to respect the safeguard.

[95] This is achieved through the continuous reporting across time of each land where a net sequestration of carbon has been accounted

[96] Be aware that in case of sub-national implementation and monitoring of REDD+ activities, the displacement of emissions at national level has to be monitored and reported. Also information on how displacement of emissions is being addressed, and on the means to integrate subnational monitoring systems into a national monitoring system have to be reported. Such information should be included in the information on the NFMS to be reported in the REDD+ technical annex of the BUR.

  - Details of national circumstances and, if the FREL/FRL has been adjusted, details on how the national circumstances were considered.
- The technical assessment, within a year from the submission, assesses (13/CP.19):
  - Transparency, completeness, consistency and accuracy of information submitted;
  - The degree of consistency of the FREL/FRL information with guidelines for its submission (as contained in 12/CP17);
  - The extent to which the FREL/FRL maintains consistency with corresponding anthropogenic forest-related GHG emissions and removals as contained in the NGHGI;
  - The extent to which the FREL/FRL value is consistent with the information submitted;
  - Whether assumptions about future changes to domestic policies have been included in the construction of the FREL/FRL.

  The technical assessment report, which is published at the end of the assessment process into the REDD+ portal of the UNFCCC (http://unfccc.int/redd), may contain areas of technical improvements, as identified by the assessment team, that developing country Parties may implement for preparing a subsequent revised version of the FREL/FRL.
- The procedure of FREL/FRL submission is built with a stepwise, iterative, approach that consist in (13/CP.19):
  - The submission of a FREL/FRL through the REDD+ portal of the UNFCCC;
  - the technical assessment, including, as appropriate, the individuation of areas of technical improvements that developing country Parties may implement for preparing a subsequent revised version of the FREL/FRL;
  - The submission[97] of a revised FREL/FRL through the REDD+ portal of the UNFCCC;

5. GHG emissions and removals

Decision 14/CP.19, plus decisions 4/CP.15, 1/CP.16, 2/CP.17 and 9/CP.19 set requirements and procedures for preparing, submitting and assessing GHG emissions and removals. In particular:

- GHG emissions and removals have to be measured for assessing the result of the implementation of REDD+ activities (1/CP.16);
- GHG emissions and removals associated with REDD+ activities are to be reported in the technical annex to the BUR (14/CP.19).
- Information to be provided in the technical annex to the BUR (14/CP.19) should be guided by the most recent IPCC guidance and guidelines, as adopted or encouraged by the COP, and:

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[97] Decision 13/CP.19 contains neither a timing for subsequent submissions of revised FREL/FRLs nor a limit to the number of revised FREL/FRL that can be submitted; although decision 12/CP.17 establishes that FREL/FRL should be updated taking into account new knowledge, new trends and any modification of scope and methodologies. It could be envisaged that because the FREL/FRL is based on historical data, revised FREL/FRL will be resubmitted as soon as the historical data used for constructing the FREL/FRL will no more be a good proxy for expected (BAU) net GHG emissions/removals in the period of implementation of the REDD+ activities.

  - Be transparent
  - Methodologically consistent over-time with FREL/FRL;
  - Be accurate, to the extent possible.
- The technical analysis assesses (14/CP.19) whether:
  - There is consistency in methodologies, definitions, comprehensiveness and the information provided between the FREL/FRL and estimates of actual GHG emissions and removals;
  - There is consistency with information reported in the NGHGI;
  - The data and information are transparent, complete, consistent and accurate;
  - The results are transparent, consistent and accurate.

The outcome of the technical analysis a technical report is published into the REDD+ portal of the UNFCCC containing: the technical annex; the analysis of the technical annex; areas for technical improvement identified; any comments and/or responses by the Party, including areas for further improvement and capacity-building needs as noted by the Party.

2.9.3 Major challenges for developing countries

Though some countries have encountered difficulties in meeting transparency and completeness of information reported, it is expected that such issues will be resolved in the following submissions as the result of countries gaining experience in reporting.. In contrast, based on the current monitoring and reporting capabilities, the principle of accuracy is presenting major challenges for most developing countries. Being accurate that estimate that fully meets the IPCC methodological good practices, and consequently it is also not affected by biases due to incompleteness. .

However, although Parties are expected to submit Forest Reference Emissions Levels and/or Forest Reference Levels from which only C pools and/or activities deemed not significant[98] can be excluded, neither in the UNFCCC documents nor in the IPCC Guidelines contain definition of significant activity.

Therefore, for REDD+ countries achieving *completeness*, in terms of C pools and activities, will clearly depend on the processes (e.g. deforestation, forest degradation, management of forests) 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[99], FAO’s FRA 2005[100]) suggests that only a very small fraction of developing countries currently reports data on soil carbon, even though emissions from soils following deforestation could be significant.

If *accurate* estimates of emissions and removals 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 GHG fluxes from deforestation is improving, in many developing countries accurate data

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[98] According to 2003 IPCC for LULUCF, significant are those C pools that contributes 25-30% of the net C stock change of the key category ; in the case of REDD+ of the REL/RL.

on deforested areas and carbon stocks are still scarce and allocating significant extra resources for monitoring may yet be difficult in the near future.

The most common issue in FRELs submitted so far has been the inconsistency in the identification of deforestation events with the IPCC and UNFCCC reporting guidelines for forest land that identify deforestation as the conversion from forest land to non-forest land uses (i.e. a permanent forets cover loss). Most Parties however have reported as deforestation any forest cover loss regardless wether it was a temporary (e.g. due to harvesting, shifting cultivation or fires) or a permanent loss. Such approach may determines an overestimation of net emissions from deforestation and also a displacement of emissions from deforestation to forest degradation/sustainable forest management in case the forest logging techniques are changed from clear cut (as in the historical period used to calculate the deforestation's FREL) to selective logging.

2.9.4 The conservativeness approach

To address the risk of potentially biased REDD+ estimates (because incomplete and/or inaccurate), and thus to increase their credibility, Grassi et al. 2008) have proposed to use the approach of *conservativeness* when comparing the performance against an agreed reference level

In the REDD+ context, conservativeness means that - when completeness or accuracy of estimates cannot be achieved - the reduction of emissions and the long-term increase of carbon stocks is not systematically overestimated so far as can be judged.

Conservativeness is present in the KP context (though not in REDD+ decisions), specifically the procedure for adjustments under Art 5.2 of the Kyoto Protocol works as follows [101]: if an Annex I Party reports to UNFCCC estimates prepared in a manner that is not consistent with IPCC guidance and that would give benefit for the Party, e.g. an overestimation of sinks or underestimation of emissions in a given year of the commitment period, or the opposite in the base year, 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 first substitutes the original estimate with a new one (generally based on a default IPCC estimate, i.e. a Tier 1) and then - given the risk of this new estimate to be biased because the quality of data is doubtful - multiplies it by a tabulated category-specific "conservativeness factor" (see Figure 4.4.1). These factors are built taking into account the uncertainty of the adjusted estimate (based on the uncertainty ranges of IPCC default values or on expert judgment). The practical effect of the application of a conservativeness factor is that the lower bound of the 50% of the confidence interval[102] is taken as the adjusted estimate, truncated in some cases to avoid very large adjustments.

Such procedure can be simply interpreted as a way to reduce the probability of the adjusted value to over-estimate the true value. Such interpretation is at the basis of many proposals to apply conservativeness, including through the RME approach; see *Grassi et al 2013* for more information.

Figure 4.4.1. 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 lower portion of the 50% confidence interval. The risk of systematically overestimating the true value, which could be high, for example, when a Tier 1 estimate is used for a

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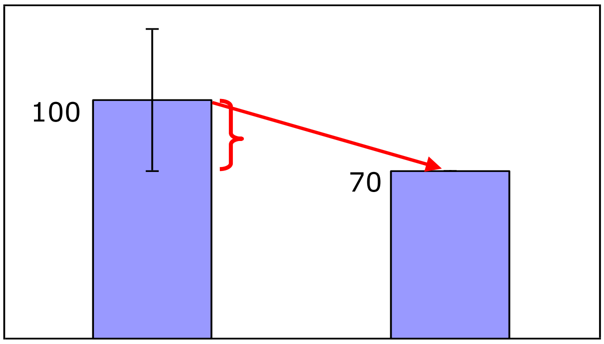
[101] UNFCCC 2006. Good practice guidance and adjustments under Article 5, paragraph 2, of the Kyoto Protocol FCCC/KP/CMP/2005/8/Add.3 Decision 20/CMP.1

[102] The confidence interval is a range that encloses the true (but unknown) value with a specified confidence (probability). E.g., the 50 % confidence interval has a 50% probability of enclosing the true value.

key category, is removed by multiplying this estimate by a conservativeness factor (in this case 0.7), derived from category-specific tabulated confidence intervals.



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.

However, although the usefulness of the conservativeness concept seems accepted in some contexts, its application to REDD+ would needs some guidance. To this end, the next two sections show two examples on how the conservativeness approach could be applied to a REDD+ accounting when data are:

(i) unavailable for a C pool, for which emissions are not increasing compared to the reference level
(ii) likely to be biased and the bias cannot be removed.

2.9.4.1 Addressing incomplete estimates

An example of incomplete estimates arises from the lack of reliable data for a carbon pool, e.g. the soil pool. In this case, being conservative in a REDD+ context does not mean "not overestimating the emissions", but 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 4.4.1) and therefore should not be considered a problem. However, this assumption of conservative omission of a pool will no longer be valid if, for a given forest conversion type, the area deforested is increased from the reference level to the assessment period; in such case, any pool which is a source should be estimated and reported.

Table 4.4.1: Simplified example of how ignoring a carbon pool can 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 (tC/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)

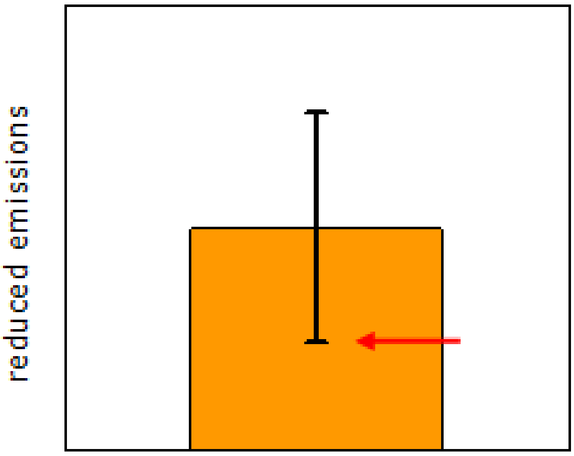
2.9.4.2 Addressing a potential bias in estimates

Assuming that during the estimation phase a Party finds evidences of a potential bias in its estimate that cannot be removed, here we suggest a possible simple approach to deal with such a problem. For instance, the country applies an IPCC default C stock value for aboveground biomass for calculating C stock losses associated with deforestation of a specific forest typology. The country is applying the IPCC default because the few data available in the country do not allow to prepare a country-specific value for that specific forest typology. However, the few available data are significantly different from the IPCC default, so that there is the risk of systematically overestimating achieved reduction in emissions from deforestation for that specific forest typology.

Similar to the adjustment procedure under Art 5.2 of the Kyoto Protocol (see above), we propose to use the 50% confidence interval in a conservative way, i.e. to remove the systematic risk of overestimating the accounted quantity. Specifically, here we briefly present a possible approach to implement this concept (more details can be found in Grassi et al. 2008 and Grassi et al. 2013):

The conservative estimate of a REDD+ accounted quantity is derived from the uncertainty of the difference between reference net emissions (REL/RL) and actual net emissions (uncertainty of the trend, IPCC 2006 GL, as illustrated in Fig. 4.4.2). Indeed, when accounting it is the uncertainty of the accounted quantity that gives information on its credibility, not the uncertainty of the individual elements of the accounting, in this case the reference level and the actual estimate. A feature 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 level and the actual estimates. In particular, if the uncertainty is correlated between the 2 elements it does not affect the % uncertainty of the trend (see Ch. 2.6.3.3 for further discussion on correlation of uncertainties). In the uncertainty analysis of the trend of GHG inventories, no correlation is typically assumed by the IPCC (IPCC 2006 GL) for activity data, and a perfect positive correlation between emission factors is assumed. Such basic assumption we consider to be applicable in most cases also in the REDD+ context.

Figure 4.4.2. The conservative estimate of REDD+ is derived from the uncertainty (i.e. the lower boundary of the 50% confidence interval) of the difference of emissions between the reference and the actual estimates (uncertainty of the trend).



The conservative correction of the REDD+ accounted quantities may be based on the uncertainties quantified by the country, when estimated in a robust way. 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).

2.9.4.3 Value of conservativeness

IPCC defines inventories consistent with good practice as those that contain neither over- nor under-estimates so far as can be judged, and in which uncertainties are reduced as far as practicable. Consequently, also REDD+ estimates should be complete (in terms of coverage of significant pools and activities) and accurate. However, once the country has carried out all the practical efforts in this direction, if there is a risk of systematically overestimating accounted quantities or estimates are incomplete the conservativeness concept can be applied to avoid that the accounted achieved mitigation be systematically over-estimated. To this end, Sections 4.4.1 and 4.4.2 provide examples of how the conservativeness approach can be applied to an incomplete estimate (e.g., an omission of a pool) and to an estimate potentially biased (when the bias cannot be removed).

Since the Bali action plan was agreed in 2007, different applications of the conservativeness approach have been proposed:

1. Conservativeness applied even if a methodology consistent with IPCC good practices has been applied and there are no evidences of potential biases. This is the approach implemented by World Bank in its FCPF Carbon Fund Methodological Framework (as in the Final version of December 20, 2013)[103]. In such methodological document when calculating emissions reductions (i.e. accounted quantities) a conservativeness factor needs to be applied, and the factor depends on the aggregate uncertainty of the estimate. Applying conservativeness in this way implies that REDD+ accounted quantities are *per se* assumed not fully comparable to, and therefore fully fungible with, estimates of other mitigation

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[103] https://www.forestcarbonpartnership.org/carbon-fund-methodological-framework

actions implemented in other sectors; conservativeness becomes the way to ensure such comparability.

2. Conservativeness applied if IPCC methods have not been fully met and/or there is some evidence of potential biases:
    a. if a methodology not fully consistent with IPCC good practices has been applied (e.g. if a Tier 1 method is used for a key category, see Grassi et al., 2013). The rationale behind this approach is that Tier 1 estimates are assumed to have inherently larger uncertainties than Tier 2 or 3 estimates; while Tier 1 cannot necessarily be assumed bias, due to larger uncertainties the risk of overestimating significantly emission reductions (thus the risk of receiving significant credits not associated to real emission reductions) is expected to be higher[104].
    b. if there is evidence of a potential bias. The rationale behind is that so far as the methodology is consistent with IPCC good practice it does not need to be adjusted, since it is accurate so far as can be judged (e.g. Federici et al., 2013). If Tier 1 is applied conservativeness is not needed, unless there is evidence that the use of IPCC default factors/parameters could overestimate in that specific conditions the achieved mitigation (i.e. emissions reductions or long-term increase in C stocks).

Where properly applied, the advantages of a conservativeness approach are the following:

- ☐ It may increase the robustness, the environmental integrity and the credibility of any REDD+ accounted quantity, by decreasing the risk that economic incentives are given to potentially biased estimates of reductions of emission. This may help convince policymakers, investors and NGOs in industrialized countries that robust and credible REDD+ estimates are possible.
- ☐ It rewards the quality of the estimates. More accurate and 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 by starting with conservativeness, precision and accuracy will tend to follow.
- ☐ It stimulates a broader participation, i.e. allows developing countries to implement REDD+ activities even if they cannot provide accurate and precise estimates for all categories and carbon pools, and thus decreases the risk of emission displacement from one country to another.
- ☐ It increases the comparability of estimates across countries – a fundamental UNFCCC reporting principle - and also the fairness of the distribution of eventual positive incentives.

2.9.5 Key references for section 2.9

Federici S., Grassi G., Achard F. (2012): Implementing the conservativeness principle in accounting for REDD+ under the UNFCCC. Published in: Mora, B., Herold, M., De Sy., V., Wijaya, A., Verchot, L. and Penman, J. 2012. Capacity development in national forest monitoring: experiences and progress for REDD+. Joint report by CIFOR and GOFC-GOLD. Bogor,Indonesia

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[104] Although the assumption of tier 1 being more uncertain may be considered generally valid, this assumption needs to be checked in each specific case. If tier 1 can be shown to be already conservative, no further conservative discount would be justifiable

Grassi G, Monni S, Federici S, Achard F, Mollicone D (2008): Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates.. *Environmental Research Letters*, 3: 035005.

Grassi G., Federici S., Achard F. (2013) Implementing conservativeness in REDD+ is realistic and useful to address the most uncertain estimates, Climatic Change (2013) 119:269–275

UNFCCC Decision 3/CP.5 Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part II: UNFCCC reporting guidelines on national communications

UNFCCC decision 17/CP.8 Guidelines for the preparation of national communications from Parties not included in Annex I to the Convention

UNFCCC decision 4/CP.15 Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries.

UNFCCC decision 2/CP.17 UNFCCC biennial reporting guidelines for developed country Parties

UNFCCC decision 2/CP.17 UNFCCC biennial update reporting guidelines for Parties not included in Annex I to the Convention

UNFCCC Decision 12/CP.17 Guidance on systems for providing information on how safeguards are addressed and respected and modalities relating to forest reference emission levels and forest reference levels as referred to in decision 1/CP.16

UNFCCC Decision 13/CP.19 Guidelines and procedures for the technical assessment of submissions from Parties on proposed forest reference emission levels and/or forest reference levels

UNFCCC decision 24/CP.19 Guidelines for the preparation of national communications by Parties included in Annex I to the Convention, Part I: UNFCCC reporting guidelines on annual greenhouse gas inventories

UNFCCC decision 13/CP.19 Guidelines for submissions of information on reference levels

UNFCCC decision 14/CP.19 Modalities for measuring, reporting and verifying

2.10 STATUS OF EVOLVING TECHNOLOGIES

John Armston, Queensland Government & University of Queensland, Australia
Sandra Brown, Winrock International, USA
Kim Calders, National Physical Laboratory & University College London, UK
Mark Cutler, University of Dundee, UK
Mathias Disney, University College London & NERC NCEO, UK
Takahiro Endo, Remote Sensing Technology Center of Japan
Michael Falkowski, University of Idaho, USA
Scott Goetz, Woods Hole Research Center, USA
Martin Herold, Wageningen University, The Netherlands
Yasumasa Hirata, Forestry and Forest Product Institute, Japan
Dirk Hoekman, Wageningen University, The Netherlands
Josef Kellndorfer, Woods Hole Research Center, USA
Richard Lucas, University of New South Wales, Australia
Eric Lambin, University of Louvain-La-Neuve, Belgium
Ronald E. McRoberts, U.S. Forest Service, USA
Rebecca Moore, Google.org, USA
Erik Næsset, Department of Ecology and Natural Resource Management, Norway
Ross Nelson, NASA-Goddard Space Flight Center, USA
Glenn Newnham, CSIRO, Australia
Ian Paynter, University of Massachusetts Boston, USA
Ake Rosenqvist, solo Earth Observation, Japan
Crystal Schaaf, University of Massachusetts Boston, USA
Svein Solberg, Norwegian Forest and Landscape Institute
Michael Wulder, Canadian Forest Service, Canada

2.10.1 Scope of section

The methods described elsewhere in this sourcebook describe approaches that can be used to estimate and report on carbon emissions and removals from deforestation and forest degradation following the IPCC guidance. New technologies and approaches are being developed for monitoring changes in forest area and carbon stocks and are described in this section. The following should be taken into account:

- The approaches have been demonstrated in project studies, and, thus, are potentially useful and appropriate for REDD+ implementation but have not yet been used *operationally*.
- They may provide data in addition to the approach described elsewhere, i.e. to overcome known limitations of optical satellite data in persistently cloudy parts of the tropics or the reduced sensitivity of radar to biomass as the latter increases (saturation).

- ☐ Data and approaches may not be available for all developing country areas interested in REDD.
- ☐ Implementation usually requires additional resources (i.e. cost, national monitoring capacities etc.).
- ☐ Further, pilot cases and international coordination are needed to further test and implement these technologies in a REDD+ context.
- ☐ Their utility may be enhanced in coming years depending on data acquisition, access and scientific developments.

The intention here is not to describe the suite of emerging technologies in detail, as reviews and summaries exist (e.g., Evans et al., 2006; Goetz and Dubayah, 2011a; Lim et al., 2003; Petrie and Walker, 2007; Hyyppa et al., 2012; Wulder et al., 2012). The discussion should increase awareness of these techniques, provide basic background information and explain their general approaches, potential and limitations (De Sy et al 2012). The options to eventually use them for national forest monitoring activities depend on specific country circumstances.

2.10.2 Airborne and satellite LIDAR observations

2.10.2.1 Background and characteristics

LIDAR (LIght Detection And Ranging) sensors use information obtained from lasers to estimate the three-dimensional distribution of vegetation canopies as well as sub-canopy topography, resulting in accurate estimates of both vegetation height, canopy structure, and ground elevation (Boudreau et al., 2008). Of special interest for REDD+ monitoring (Herold and Johns 2007), LIDAR is the only remote sensing technology to provide metrics that have no apparent saturation with increasing biomass (Drake et al., 2003). LIDAR systems are classified as either full waveform or discrete return sampling systems, and may further be characterized by whether they are profiling systems that record only along a narrow transect, or scanning systems that record across a wider swath. Full waveform sampling LIDAR systems generally have a coarser horizontal spatial resolution with footprints on the order of 10 – 70 m combined with fine and fully digitized vertical spatial resolutions, resulting in full sub-meter vertical profiles. Although there are currently no operational systems that provide large-footprint full waveform LIDAR data, the Geoscience Laser Altimeter System (GLAS) onboard the NASA Ice, Cloud and land Elevation Satellite (ICESat) was extensively used for characterizing forests and developing generalized products for modelling. This system was operational from 2003-2009, and provided the first global LIDAR data used for capturing forest structure. Data from GLAS were used to estimate forest canopy height for the globe (Lefsky 2010, Simard et al. 2011) and aboveground biomass for the tropics (Baccini et al. 2012; Saatchi 2011). Each GLAS pulse illuminated an approximately circular footprint of ~65 m diameter with an along-orbit distance between shots of 172 m and a maximum distance between adjacent orbits of ~30 km at the equator. The third and final laser on ICESat I / GLAS failed on October 19, 2009, and the satellite was deorbited on 30 August 2010. These GLAS-based global height maps used a single estimate of height for a cell size of 1 x 1-km (Simard et al. 2011) or for segments with a minimum cell size of 500 x 500-m although typically larger (Lefsky 2010). Although these coarse height maps are informative at the global, or regional scale, their utility for REDD+ applications is yet to be determined or demonstrated.

A higher-resolution set of height and structure observations will be provided by the upcoming Global Ecosystem Dynamics Investigation (GEDI) mission, which will launch a 3-laser system to the International Space Station (ISS), and capture full waveform LIDAR returns with a planned nominal circular footprint of ~25 m. GEDI, a NASA mission led by the University of Maryland, will be the first spaceborne LIDAR mission specifically designed to study forests. From the ISS, GEDI will capture data between ~51.5 degrees North and South. GEDI's three lasers will operate at 1064 nm, the same near infrared wavelength used by GLAS and most other LIDAR systems used to study forests. One laser will be a full power laser, while two will be split into two beams each, producing lower energy pulses but allowing for greater spatial coverage. Each laser will be optically dithered, resulting in 10 ground tracks with ~600 m spacing between tracks, and ~60 m between footprints along each track. GEDI products will be generated both at the footprint (25 m) level and gridded (1 km) level. Products will include geolocated waveforms, ground elevation, canopy height, relative height metrics (percentiles above ground), canopy cover, LAI, and aboveground biomass. GEDI currently has a planned launch date of December, 2016. Although GEDI will provide global observations at a relatively high resolution for spaceborne data (25 m), discrete return airborne LIDAR will continue to provide the highest resolution information on forest structure at a local-regional scale.

Discrete return LIDAR systems with small footprints on the order of 0.1 – 2 m in diameter typically record one to five echoes per emitted laser pulse and are optimized for estimation of terrain surface elevations with sub-meter accuracies. These systems are used commercially for a wide range of applications including topographic mapping, power line right-of-way surveys, engineering, and natural resource characterization. Discrete return scanning LIDAR yields a three-dimensional cloud of echo heights (echoes), with the lower heights representing the ground and the upper heights representing the canopy. One of the first steps undertaken when processing LIDAR data involves separating ground and non-ground or canopy echoes. This task is often undertaken by LIDAR data providers using software such as TerraScan, LP360, or the data provider's own proprietary software. Analysis can commence once all LIDAR echo heights have been classified into ground or non-ground echoes. Ground echoes are typically gridded to produce a bare earth Digital Elevation Model (DEM) using standard software approaches such as triangulated irregular networks (TIN), nearest neighbour interpolation, or spline methods. Because the horizontal point spacing of the LIDAR observations is substantially finer than the spatial detail typically observable on aerial photography, the DEMs estimated from LIDAR often contain substantially more horizontal and vertical resolution than elevation models estimated from moderate scale aerial photography (Lim et al., 2003).

2.10.2.2 Experiences for monitoring purposes

Research and development activities have so far focused on using LIDAR as a source of data for predicting vertical forest structure - primarily the prediction of tree and stand heights, with volume, biomass, and carbon also of interest (Hyyppa et al. 2012). With increasing availability of LIDAR data, forest managers have seen opportunities for using LIDAR to satisfy a wider range of forest inventory information needs. For instance, height estimates obtained from airborne remotely sensed LIDAR data have been found to be of similar, or better accuracy than corresponding field-based estimates. Further, LIDAR measurement errors are less than 1.0 m for individual tree heights of a given species and less than 0.5 m for plot-based estimates of maximum and mean canopy height with full canopy closure. Additional attributes including volume, biomass, carbon, stem density, crown closure, and multiple measures of forest structural diversity (Mura et al., 2015) are also well characterized with LIDAR data.

Scanning LIDAR is typically used to collect data with full geographical or wall-to-wall coverage for an area of interest. Forest inventories that provide detailed information for individual forest stands for planning and management purposes are rapidly becoming a standard method for territories with sizes of 50-50,000 km^2. Since 2002, scanning LiDAR has been used operationally for these stand-based forest management inventories (Næsset 2004b) in many countries on all continents, especially in boreal forests and plantations. In the Nordic countries, it is the preferred method. Scanning LIDAR technology is currently being used or tested globally for operational inventories, pre-operational trials, or to estimate project specific subsets of forest attributes including biomass.

A basic requirement for inventory and monitoring of forest resources and biomass is the availability of ground measurements obtained from field plots. Ground measurements are required to estimate relationships between the three-dimensional properties of the LIDAR point cloud such as height and density metrics and summary statistics and the target biophysical properties of interest such as biomass, using parametric or non-parametric statistical techniques (Section 2.3). Once such relationships have been estimated, the target biophysical properties can often be predicted with considerable accuracy for the entire area of interest for which LIDAR data are available. The technology may be used for local REDD+ projects within the countries following the same procedures as used for management inventories in boreal and temperate forests and plantation forests. Data from scanning LIDAR, although considered to be expensive, may be more cost-effective for biomass estimation than free or almost free data from satellite remote sensing such as InSAR when the uncertainty of the estimates is considered (Næsset et al., 2011). Because LIDAR data are highly correlated with biophysical properties such as volume and above-ground biomass and thus carbon, surveys using LIDAR data as auxiliary information may require less intensive ground sampling to obtain the same precision of estimates as other remote sensing technologies.

For monitoring larger territories such as provinces, nations, or even across nations, profiling as well as scanning LIDAR instruments can even be used in a sampling mode. With this approach, two-stage or two-phase sampling designs are used whereby LIDAR data are acquired along selected strips corresponding to aircraft flight lines separated by many kilometers, depending on the desired sampling intensity, with subsequent ground sampling along the strips or from another area (Nelson et al. 2003, Næsset 2005). Optical remotely sensed imagery and other spatial data can be used to aid stratification, inform sampling and enhance estimation (Wulder et al. 2012). Thus, LIDAR data can be used to provide a conventional sampling-based statistical estimate of biomass or changes in amount of biomass over time. A sample consisting of conventional 300-m^2 ground plots at a 10x10-km spacing produces a sampling intensity of 0.0003%, whereas a sample of scanning LIDAR data collected along strips flown over the same field plots will produce a sampling intensity of 5-10% of the population. Because biomass and canopy properties and LIDAR data are highly correlated, the combination of LIDAR and field data has been shown to improve the precision of estimates based on field data only or to reduce costs by reducing the number of field measures necessary to achieve the same level of precision.

Biomass assessments for larger areas in tropical forests have recently been reported and are the subject of substantial interest in the context of REDD+ (Baccini et al. 2011, Saatchi et al. 2010, Houghton 2013). In addition, a meta-analysis of multiple experiments with airborne LIDAR in tropical forests documents strong relationships between biomass and other biophysical properties and LIDAR data (Zolkos et al. 2013). Unlike other remote sensing techniques, such as optical remote sensing and SAR, LIDAR does not suffer from saturation problems associated with large biomass values. LIDAR has been shown to be capable of discriminating among biomass values as great as 1,300 Mg ha^{-1}. Thus, airborne and spaceborne LIDAR have great potential as sampling tools across forests globally (Goetz and Dubayah 2011a, Wulder et al. 2012).

2.10.2.3 Monitoring costs

Monitoring costs when using airborne LIDAR are variable. In general, users can expect some elements of the cost structure to be similar to those for air photo acquisition, including flying time and related fuel costs (Wulder et al. 2008). Further, economies of scale, whereby larger project areas can lead to a reduction in per unit area costs, are likely. Large acquisition areas mean less time turning the aircraft and more time actually acquiring data. Processing to meet project specific information needs will also result in additional costs. Reported costs for LIDAR surveys vary widely. In Europe, costs for LiDAR data collection for operational forest inventories are currently in the range of \$0.5-1.0 per hectare when the projects are of sufficient size. Prices in South America using local data providers such as Brazilian companies are typically greater. The situation is likely to be the same in Africa using local data providers such as those from South Africa. Recent bids for complete, wall-to-wall LIDAR coverage for a REDD+ demonstration in Tanzania from European data providers were on the order of \$0.5-1.0 per hectare. When LIDAR is used to sample a landscape on the order of 1,000,000 km^2, a marginal cost per km of flight line of ~\$30-40 can be anticipated in regions such as eastern Africa. Thus, a 1% sample of such a landscape using a 1-km swath width should be feasible for a total cost of approximately \$300,000-400,000. When comparing costs, the utility of the data must also be considered. In particular, airborne LiDAR technology may be more cost-effective than other remote sensing technologies, even when data are acquired free of charge, because fewer field observations may be needed to satisfy a specified precision level (Næsset et al. 2011).

2.10.2.4 Contribution of LIDAR to existing IPCC land sector reporting

Detection and characterization of degraded forests is often difficult. Optical remotely sensed data is a key data source for capturing some aspects of change and can be related to degradation. Because LIDAR data can be used to estimate the vertical distribution and structure of forests, integrating LIDAR and optical remotely sensed change data can be used to estimate the carbon consequences associated with such change. The free and open Landsat archive offers opportunities for constructing large area composites (Hansen and Loveland 2012) and change detection in tropical environments (Potapov et al. 2012). Further, novel data processing of time series optical data, integrated with LIDAR data, have been shown to be useful for describing forest structure and succession and for improving attribute characterization (Hansen and Loveland 2012, Pflugmacher et al. 2012, Potapov et al. 2012).

LIDAR is becoming an important source of data for estimating changes in tropical forests. The requirement to report on changes in carbon stocks by activities, such as deforestation and degradation, is difficult to satisfy with acceptable precision with most remote sensing technologies. LIDAR is a technology that advances monitoring capacity for tasks such as distinguishing changes in biomass and carbon stocks in temperate (Huang et al. 2013) and tropical (Dubayah et al. 2010; Meyer et al. 2013) biomes. There is a longer history of documenting boreal forest change discrimination with LIDAR, even among different types of changes (Næsset et al. 2013).

LIDAR's fine vertical and horizontal resolutions also facilitate fine-scale, field plot-like predictions. Although the uncertainty in these predictions must be accommodated, the predictions can be used to calibrate and validate model outcomes, to inform the carbon consequences of deforestation and degradation, and to locate and enable characterization of forest gaps introduced over time. When assessing the utility of LIDAR measurements, consideration must be given to the REDD+ context and information needs including the value of increased accuracy and precision of measures and/or the ability to better characterize error budgets associated with mapped or estimated measures.

2.10.2.5 Design, modeling and estimation for LIDAR surveys

Multiple modeling approaches have convincingly demonstrated the utility of LIDAR data for estimating forest attributes, particularly attributes such as volume and biomass. Models of relationships between forest attributes and LIDAR data are commonly constructed using a combination of field plot observations and geo-referenced LIDAR metrics.

Little empirical information on plot configurations and sampling designs that are optimal for joint acquisition of field and LIDAR model training data is available, particularly for tropical forests. Although the relatively sparse results for boreal and temperate forest studies may not be definitive for tropical applications, they may still provide useful guidance. When data from field plots and LIDAR sensors are combined, co-registration to a common coordinate system is crucial. For forestry applications, GPS location accuracy is known to increase with decreasing forest density and height, increasing observation period, number of satellites, and greater satellite distribution. In addition, for a positional error of a specified magnitude, the adverse effects are less for more homogeneous forest conditions, less fragmented forests, circular plots as opposed to rectangular plots of the same area, and larger plots.

Plot boundary effects arise because field plot assessments of tree variables are based on stem locations, whereas LIDAR assessments are based on the vertical extensions of the plot boundaries. Thus, portions of trees whose stems are outside plots may extend into the vertical extensions of plot boundaries and, similarly, portions of trees whose stems are inside plots may extend beyond the vertical extensions of plot boundaries (Mascaro et al. 2011, Næsset et al. 2013a). The effects of these discrepancies are to obscure relationships between field measurements and ALS metrics and to impede construction of accurate models. The effects can be reduced using larger circular plots because their ratios of circumference to area are less than for smaller or rectangular plots and using larger plots relative to the sizes of tree crowns. However, whereas circular plots are generally used for boreal and temperate forests, rectangular plots have been traditional in some tropical countries to accommodate other concerns (Kleinn 2003, McRoberts et al. 2013) and have been recommended by FAO (Saket 2002).

A fundamental concept underlying many LIDAR modeling efforts is that the three-dimensional LIDAR point cloud contains information that can be used to estimate the vertical distribution of vegetation. Magnussen and Boudewyn (1998) showed that the proportions of LIDAR heights at or above given reference heights were useful predictors of forest attributes. A crucial extension of this seminal result is that pulse densities for spatial units must be sufficiently large to produce reliable estimates of the parameters of the LIDAR height distributions used as model predictor variables. For boreal and temperate studies, minimum pulse densities have rarely been less than 0.1 pulses / m^2 (Næsset 1997b, Holmgren 2004), and minimum plot areas have rarely been less than 200 m^2 (Næsset 2002, Andersen and Breidenbach 2007, Gobakken and Næsset 2008, Breidenbach et al. 2008, Maltamo et al. 2011). Although many of these results are not directly comparable because the pulse density studies did not use common plot areas and vice versa, when the results are expressed in terms of pulses per plot, pulse densities of 100 – 225 pulses per plot were sufficient. Presumably, these densities would constitute only a minimum threshold for tropical studies.

Because ground sampling is an expensive enterprise, many approaches to remote sensing-based estimation attempt to capitalize on existing sampling programs such as those conducted by national forest inventories (NFI) to acquire ground training and accuracy assessment data. However, use of data acquired from existing sampling programs permits few opportunities for optimization, because these plot configurations and sampling designs were generally not developed to support remote sensing-based studies and are not easily modified once implemented.

For many applications, complete coverage of LIDAR data using airborne sensors would be prohibitively expensive. The result is that for large area applications, LIDAR data acquired from airborne sensors are commonly obtained in strips corresponding to straight aircraft flight lines. When the LIDAR data are to be combined with ground data acquired using systematically distributed ground plots established by programs such as NFIs, the strips often follow the systematic grid lines corresponding to the field sampling designs. When the LIDAR acquisition does not depend on an existing field sampling design, the strips may be either randomly or systematically distributed over the study area, and the ground plots may be established exclusively within the LIDAR swaths.

When feasible, optimization of ground sampling designs for the specific purpose of acquiring LIDAR calibration data for constructing models may produce positive results. Næsset (2002, 2004a) stratified on age class and site quality to accommodate differences in LIDAR height distribution of LIDAR heights as means of improving models. Hawbaker et al. (2009) and Gobakken et al. (2013) compared simple random and stratified sampling designs using strata with similar means and standard deviations of the LIDAR height distributions. The stratified design distributed sampling locations more uniformly with respect to the height distributions, produced more observations in the tails of the distributions, and required fewer extrapolations beyond the range of the LIDAR sample data when the model was applied to the entire population.

The utility of models is not realized until they are used to produce maps or to produce or enhance area-based estimates. For mapping and area-based estimation purposes, the models are used to predict the attribute of interest for spatial polygons that tessellate the study area. Næsset (1997a,b) initiated the practice of tessellating study areas into grid cells with the same size but not necessarily the same shape as field plots, predicting the response variable for each grid cell, and calculating the mean over grid cells as an estimate for the entire study area or at least the portion of the study area with LIDAR coverage.

Full realization of a model’s utility requires inferences in the form of confidence intervals for the LIDAR-based estimates for large multi-cell areas rather than just map accuracy measures for categorical forest attribute variables or model root mean square errors for continuous variables. For construction of confidence intervals, unbiased or at least nearly unbiased estimators for totals and means and estimators of variances are necessary. Of importance, the estimators must be correctly matched to the LIDAR sampling design with the result that the complexity of the estimators is directly related to the complexity of the sampling designs.

Two approaches to inference may be considered for LIDAR applications. A crucial assumption underlying the more familiar design-based inference is that a probability sample of population units is acquired using a randomization approach. When complete coverage, wall-to-wall LIDAR data are acquired, inferential procedures are statistically less complex. Using a model of the relationship between volume and LIDAR metrics, McRoberts et al. 2012a) constructed a volume map, aggregated the map predictions into small numbers of strata, and used a design-based, post-sampling stratified estimator to decrease the variance of the plot-based mean by a factor greater than 3. A more efficient use of the LIDAR data is with the design-based, model-assisted regression estimator whereby an initial estimate calculated as the mean over all LIDAR cell predictions is adjusted to compensate for systematic model prediction error (Næsset et al. 2011). McRoberts et al (2012b) obtained variance reduction by a factor greater than 4.5. For partial LIDAR coverage in the form of strip samples, the design-based statistical estimators are more complex because uncertainty from multiple sources must be accommodated in the variance estimators (Gregoire et al. 2011; Andersen et al. 2011).

The assumptions underlying model-based inference are quite different than the assumptions underlying design-based inference. In particular, model-based inference may use, but does not require, a probability sample. In this regard, model-based inference may be an attractive inferential alternative for remote and/or inaccessible regions for which probability sampling is either logistically or economically not feasible. McRoberts et al. (2012b) and Ståhl et al. (2011) illustrate the basic features of model-based inference. However, model-based inference is sensitive to model lack of fit, because, contrary to design-based model-assisted inference, the estimator includes no adjustment for estimated bias resulting from systematic prediction error.

For many REDD+ applications, biomass change over time is the primary forest attribute of interest. Direct approaches for mapping biomass change use a single set of field observations of change and two sets of LIDAR data. A model of the relationship between the change observations and metrics obtained from the combined sets of LIDAR data is used to predict change for each grid cell. Indirect approaches use two sets of field observations and two sets of LIDAR data. A model of the relationship between biomass and the LIDAR metrics for each year is used to construct a biomass map. A biomass change map is constructed by comparing the two biomass maps. Inference based on maps constructed using the direct approach require a reference set consisting of change observations, whereas inference based on maps constructed using the indirect approach can use either a reference set consisting of change observations or two reference sets each consisting of biomass observations (Bollandsås et al. 2013, Næsset et al. 2011, 2013). Regardless of the nature of the reference sets, they must be acquired using probability sampling designs.

2.10.2.6 Data availability and required national capacities

Both airborne and spaceborne LIDAR data are available. The airborne data source can be considered globally available, with coverage on-demand, procured via contracting with commercial agencies on a global basis. Although initial LIDAR data applications focused on utility corridor characterization and elevation model development, operational forest characterization has also become quite common. Spaceborne LIDAR data are also available globally through the production of global information products based upon GLAS data that are freely available through the National Snow and Ice Data Center, NSIDC.

The theoretical global availability of airborne LIDAR data is not entirely analogous with the global availability of LIDAR data acquired via a satellite platform. When data are collected from a satellite platform, especially by an agency with a free and open access data policy, reasonable expectations are that the data are collected in a systematic manner, have known and documented coverage, are processed in a consistent fashion, and are appropriate for uniform spatial applications. Although airborne data could theoretically be collected anywhere, costs are typically greater for more unusual locations and where implementation of the survey is more difficult. Airborne data can be collected by a variety of instruments, over a range of settings, resulting in data with varying qualities. A global collection enterprise using low flying aircraft would require agreements and / or participation of national agencies. Many nations are unlikely to allow external parties to collect LIDAR data over their jurisdictions. Although not to belabor the point, airborne data are a valuable source of information on vertical forest structure and should continue to be availed upon, but the goal of spaceborne LIDAR instruments aimed at vegetation characterization should notbe surrendered. The REDD+ community is an important voice advocating for satellite-based laser missions.

The required national capacity for using LIDAR data can be great when analysis from data capture through to information generation is desired; conversely, capacity needs can be less if a contract-based approach is pursued. National end users can contract for the desired information outcomes from the LIDAR acquisition and processing provider. Thus, clear information needs that can be used to develop statements of work and deliverables for contractors are important. Information needs to satisfy REDD+ criteria can be developed for LIDAR applications that are analogous to those under development for field data.

2.10.2.7 Status, expected near-term developments and long-term sustainability

There is currently no operational space laser. However, the United States is working toward development of a new spaceborne LIDAR mission to be flown on ICESat II. The instrument, called a photon counter, will be of a fundamentally different design than the instrument on ICESat I, and its utility for estimation of vegetation structure, height and biomass is currently unknown. Although specific mission details are dynamic, ICESat II is expected to launch in 2016. Assuming this launch date doesn’t slip, there will likely be a 8-9 year data gap between the ICESat I and ICESat II missions. A LIDAR Surface Topography mission (LIST) to collect global LIDAR data over a 5-year mission is also planned for launch in the 2020s. LIDAR data acquired by LIST will have a footprint size and along and across-orbit point spacings of 5 m. In addition to having a substantial data gap between ICESat I and the ICESat II, the proposed missions are likely to provide different LIDAR data than are currently available. Thus, comparison and cross calibration efforts are currently underway using simulator instruments flown on aircraft.

Nelson et al. (2012) presented work on the use of a profiling airborne LIDAR instrument to enhance sample-based estimates of area-wide forest resources. This research rests upon a statistical framework proposed by Ståhl et al. (2011) and improved upon by Ene et al. (2012; 2013). The research is informative insofar as all space LIDARs that are being proposed or currently built for launch in the 2010s are either single beam (e.g., LEAF) or multi-beam (e.g., ICESat II, GEDI, FLORESTA) profilers. These space profilers will be used as sampling tools to augment and spatially extend ground plot observations that are not necessarily part of a probability-based ground inventory. The Ståhl et al. (2011) and Ene et al. (2013) model-based sampling frameworks may be applied to the data collected by these space profilers (assuming that one or more make it to orbit) because the methodology does not require co-location of the LIDAR sample profiles with a probability-based sample of field plots in order to calculate statistically robust estimates of variance. In fact, one underlying assumption of Ståhl's approach is that the LIDAR sample profiles and the ground plots are independent. To be clear, spatially coincident space laser measurements and ground plots are necessary in order to construct predictive models, but these coincident laser-ground observations do not have to be, in fact, should not be, part of the LIDAR sample profiles. As long as the coincident space laser and ground observations are representative of the entire population of interest, these coincident observations can be located anywhere, even outside the boundaries of the area of interest (though this option is not recommended).

2.10.2.8 Applicability of LIDAR as an appropriate technology

Although LIDAR is an emerging technology in terms of large-area monitoring, especially within the nascent REDD+ processes (see De Sy et al. 2012), it is well-established as a data source for contributing to satisfaction of forest management and science objectives. The capacity for LIDAR to characterize biomass and biomass change over time positions the technology well to meet REDD+ information needs (Goetz and Dubayah 2011a). The information need and the actual monitoring framework used may further guide application of LIDAR for national carbon accounting and reporting purposes. The actual costs to a program need to be vetted against the information that is acquired, how this information meets the specified needs, and importantly, the degree to which the reduction in uncertainty from LIDAR-based estimates offsets initial costs. Pilot studies and international coordination of on-going and proposed activities to meet REDD+ information needs are encouraged. Although LIDAR data are currently available in a limited manner from spaceborne platforms, an increase in this capacity is envisioned and urgently needed. The possible limitations in spaceborne measures are only partially offset by the widespread and operational acquisition of LIDAR from airborne platforms.

2.10.2.9 REDD+ and forest biomass monitoring based on InSAR from Tandem-X satellite data in Norway and Tanzania

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A method for REDD+ MRV is being developed based on studies in Norway and in Tanzania. The idea is based on the relationship between Above Ground Biomass (AGB) and InSAR height derived from bi-static SAR satellite acquisitions such as from the Tandem-X satellite mission. For REDD+ the changes in AGB, and in forest Carbon, is derived directly from InSAR height changes. Together with coherence data the different categories of forest change can be mapped. A business-as-usual (BAU) reference can be derived by combining SRTM from 2000 and Tandem-X from 2011. The results are fairly accurate and correspond well to results obtained with airborne laser scanning.

In Norway the studies have been carried out in forests dominated by Norway spruce. It has been shown that Tandem-X can be used for mapping of AGB with an accuracy of 57 t/ha (43 %) for 250 m^2 plots and 25 t/ha (19 %) at the stand level (Solberg, Astrup et al. 2013). Further, it has been shown that eleven year changes from SRTM to Tandem-X can provide estimates of AGB changes, with only slightly lower accuracy (Solberg, Næsset et al. 2014). Maps of AGB changes based on InSAR height changes corresponded well to maps based on ALS data (Fig. 1). At the same time, the methods are being tested in Tanzania, where we have one study area in a miombo savannah forest (Solberg, Gizachew et al. 2015), and another in an evergreen, very-high biomass mountain area. We have developed a correction from C- to X-band InSAR height, which has provided a simulated X-band SRTM DEM from 2000. In this way the changes from 2000 to 2011 should be unbiased. In these studies we estimated AGB from linear, no-intercept models, i.e. where AGB was proportional to InSAR height. A striking result of this was that the slope, or proportionality, was similar in the spruce forest from Norway (14.8 t/ha/m) and the two very different forest types in Tanzania, i.e. 13.6 t/ha/m in the miombo savannah and 16.8 t/ha/m in the evergreen forest. This indicates that an almost generic parameter value of 15 t/ha/m exists, and that such a value could be used without much error in cases with a lack of field inventory and calibration.

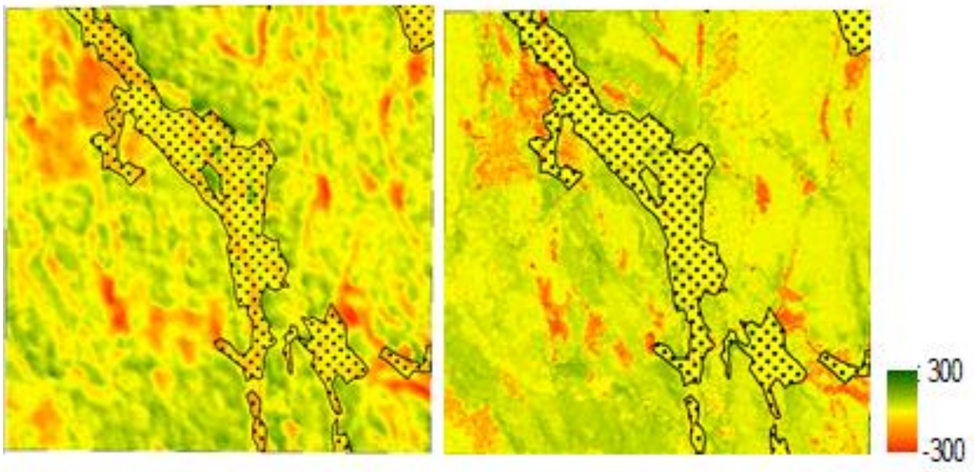

Fig. 2.10.2.9.1. Predicted AGB change (t/ha) over the study area in Våler, Norway, based on height changes from SRTM X-band to Tandem-X (left) with the model AGB = 14.9IH (left), and based on repeated ALS acquisitions (right). Agricultural fields are outlined and marked with black dots. From (Solberg, Næsset et al. 2014).

A further refinement of the method for REDD+ is to assign temporal changes to categories of forest change (Fig. 2). The categories presented here were generated by combining changes in InSAR height and coherence. For example, deforestation is characterized by a severe reduction in height, in comparison to the actual forest heights in the area, and a high coherence value which indicates little or no remaining vegetation. In comparison, forest degradation means in most cases a smaller height reduction, while the coherence remains at a low value. The map of change categories fitted well to results obtained with optical imagery as seen in the Global Forest Watch (Hansen, Potapov et al. 2013). However; more categories are obtained with InSAR data, and of particular value is that the InSAR based method can detect both degradation and forest growth.

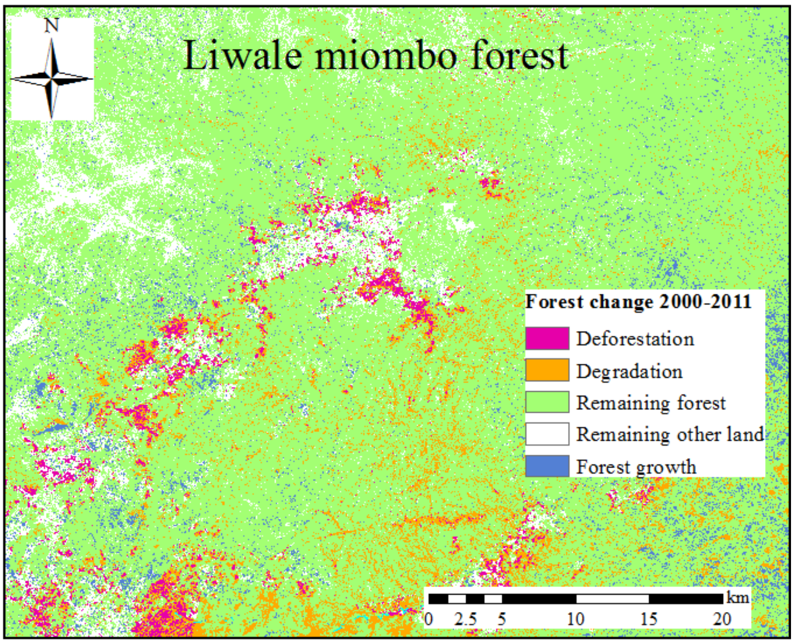

Fig. 2.10.2.9.2. Forest change categories for the period 2000 – 2011 in a miombo savannah forest in Tanzania. The categories are based on InSAR height and coherence data from SRTM and Tandem-X (Solberg, Gizachew et al. 2015).

In these studies we used three types of data: Field inventory, airborne laser scanning (ALS) and InSAR data from SRTM and Tandem-X. The field data were carried out in plots that were accurately positioned using differential GPS / GLONASS. The measurements comprised diameter at breast height on all trees above a certain minimum threshold and height on a sample of trees. In addition tree species was recorded. Allometric models were used to derive AGB and Carbon data from the field data. The ALS was used primarily to obtain a Digital Terrain Model (DTM). The DTM was subtracted from the Digital Surface Model (DSM) derived from InSAR data. We would like to stress here that the DTM is not required for an operational REDD+ MRV, because the AGB and Carbon can be determined directly from InSAR height changes. The DTM was used partly because it enabled more detailed research, and partly to obtain terrain elevation at the field plots as part of the AGB – InSAR height modelling. The SRTM data used included both X- and C-band DSMs, and both the 1 and the 3 arcsec data. The results from Norway, where we have access to full areal coverage with all these 3 data sets, indicated that the accuracy and results in general was almost negligibly influenced by which of the SRTM data sets we used. For Tandem-X we used co-registered data pairs in single look complex format (CoSSL), as received from the German Aerospace Center (DLR) and Airbus Defense and Space. They were processed into InSAR DSMs, step-by-step through generation of interferograms, differential interferograms obtained relative to a reference DEM, noise filtering, phase unwrapping and phase-to-height conversion and geo-coding into 10 m x 10 m resolution.

The results for AGB estimation, and for the corresponding standing volume, obtained with Tandem-X were similar to the results based on SRTM (Solberg, Astrup et al. 2010, Solberg, Astrup et al. 2010). We have also tested radargrammetry based on TerraSAR-X stripmap imagery, and obtained almost identical results and accuracies as with Tandem-X in a spruce forest in Norway (Solberg, Riegler et al. 2015). Hence, stripmap X-band radargrammetry might be an alternative technology in case bi-static SAR should not be available in the future. However, radargrammetry required more acquisitions to obtain the same accuracy as with Tandem-X. It has also been shown that logging can be derived from repeated SAR acquisitions, either based on radargrammetry (Deutscher, Perko et al. 2013), or by InSAR (Solberg, Astrup et al. 2013).

A key requirement for applying InSAR, or radargrammetry, in the way described here is that the InSAR heights do not vary randomly over time. Variation in weather conditions, in particular moisture and frost – non-frost, as well as seasonal variations in phenology, might influence the penetration depth of the SAR microwaves down into the vegetation. We have found that in a Norwegian spruce forest in Norway frost had a considerable effect on InSAR height, while InSAR height stayed almost constant during various weather conditions in the frost-free period spring – summer – autumn (Solberg, Weydahl et al. 2015). Also, a similar study from a tropical rainforest has shown very stable InSAR height values during 10 acquisitions over 2.5 years in Indonesia (Solberg, Lohne et al. 2014).

2.10.2.10. References

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2.10.3 Terrestrial LIDAR for forest monitoring

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2.10.3.1 Background

Terrestrial LIDAR, also called terrestrial laser scanning (TLS), is a ground-based remote sensing system that can measure 3D vegetation structure (i.e. the size and location of canopy elements) to centimeter or even millimeter accuracy and precision. Broad scale mapping based on remote sensing (satellite) data rarely, if ever, record the type of forest structural and dynamic information we require directly. Various simplifying assumptions, models and ancillary data are typically required to extract such information. At the fine (sub-ha plot) scale, it has also been difficult to incorporate rapid and robust assessment of accurate ground reference data of 3D forest structure into existing surveying and mapping strategies. This is in part due to the relative newness of such detailed structural data and the consequent lack of consistent methods for processing and analysing these data in conjunction with more traditional survey and monitoring methods. The potential of TLS for forest monitoring was first demonstrated more than a decade ago, but has not yet reached its full potential, for the reasons outlined above. Newnham et al. (2015) & Anderson et al. (2015) provide a full review of the development of TLS as a forest measurement tool.

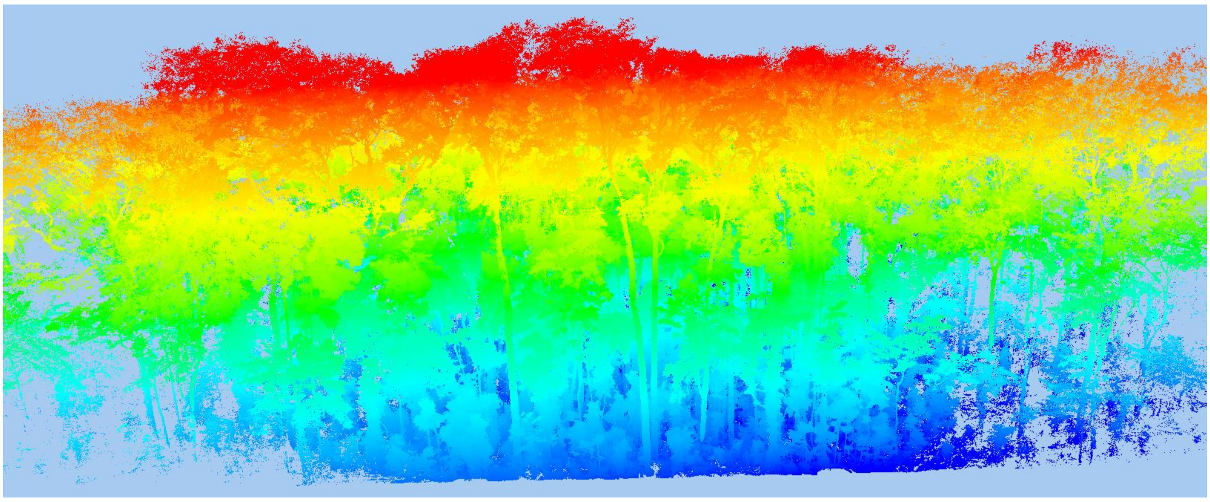

Figure 2.10.3.1.1: Illustration of a 3D TLS point cloud of a Maranthaceae forest in Lopé National Park located in central Gabon. The data were collected with a RIEGL VZ-400 from 7 different scan locations. Coloured by height (blue = 0 m; red = 45 m).

Terrestrial LIDAR sensors are usually tripod mounted and record single scans from a fixed location. As such, scans are affected by occlusion, i.e. the near objects in the forest can obscure objects further from the scanner. The effects of occlusion can be significantly reduced by obtaining data from multiple scan locations. Multiple single scans made at different locations can be co-registered (to within mm accuracy depending on instrument and environment) using high reflectivity targets that act as tiepoints between different scans (see ***Figure***). A range of scientific and commercial scanners are currently available. Whereas airborne LIDAR systems have been used in forest measurements since the mid-eighties (Nelson et al., 1984), the first commercial terrestrial laser scanners came to the market in the late 90s with instruments such as the RIEGL LMS Z210 and CYRAX 2200. The first TLS instruments used a time-of-flight ranging principle, with phase-shift based ranging instruments following soon after. The commercial instruments were (and still are) generally developed for precision mapping and survey applications where hard targets (i.e. structurally continuous surfaces) dominate e.g. urban areas and/or mineral and petrochemical exploration. This has implications for their use in forest applications, where many laser hits are partial, and/or from softer targets (i.e. structurally fragmented or dispersed surfaces) with anisotropic reflecting surfaces such as leaves or needles and bark. Of the scientific (i.e. non-commercial) scanners, the Echidna Validation Instrument (EVI) was one of the first laser scanners specifically designed to monitor vegetation (Strahler et al., 2008). Commonly used commercial instruments include the RIEGL VZ-series, Leica C10 and HDS7000, Optech ILRIS-HD and FARO Focus^{3D} X 330 and Trimble TX8 (see ***Table 1***). Newnham et al. (2012) provide a detailed independent comparison between some commercial scanners and evaluated their performance for measuring vegetation structure.

Table 1: Overview of commonly used commercial TLS instruments

Instrument	**RIEGL-VZ400**	**Leica C10**	**Leica HDS7000**	**Optech ILRIS-HD**	**FARO Focus^{3D} X 330**	**Trimble TX8**
Ranging method	Time-of-flight	Time-of-flight	Phase-shift	Time-of-flight	Phase-shift	Time-of-flight
# returns	Multiple	Single	Single	Single	Single	Single
Wavelength [nm]	1550	532	1500	1535	1550	1500
Range [m]	0.5 – 350 (high speed) 0.5 – 600 (long range)	0.1-300	0.3-187	3 – 1250	0.6 - 330	0.6 - 120
Samples/sec	42,000–122,000	50,000	101,6000	10,000	122,000-976,000	1,000,000
Beam Divergence [mrad]	0.3	0.1	< 0.3	0.150	0.19	0.177
Weight [kg]	9.6	13	10	14	5.2	11
Temperature range [deg C]	0 - 40	0-40	0-45	-20 – 40	5 – 40	0-40

2.10.3.2 Reducing uncertainties in forest monitoring

Uptake of terrestrial laser scanning for operational forest monitoring has been slower compared to airborne laser scanning (ALS). This is despite its potential to assess forest structure in more detail than traditional forest survey techniques. This is in part due to the novelty of the measurements: foresters are understandably reluctant to abandon (or compromise) tried and tested metrics for relatively unproven new metrics, even if these latter are likely to prove much more accurate and/or illuminating. Nor should they; TLS methods can augment existing methods, but continuity of measurement is also very important, particularly for historical comparisons. A second reason for the relatively slow adoption of TLS as a management tool is that, compared to ALS, it covers much less ground. Also, TLS may appear slower and/or more expensive than traditional surveying methods (although this is often not the case in practice).

The focus of TLS in the past 15 years has been to present a more objective and robust tool to measure forest structural metrics that are historically accepted for inventories. To some extent this does not exploit the detailed vegetation structural information contained in terrestrial LIDAR scans. Two general modeling approaches are used to derive forest metrics from the acquired 3D data: gap probability and geometric modeling. Measurements of the vertical and horizontal distribution of vegetation are used to describe the gap probability, which is defined as the probability of a beam with infinitesimal width being able to penetrate through the canopy, along a given trajectory and distance. This has been the basis for estimating plant area index (PAI, defined as the one-sided area of plant material surface per unit ground surface area) from ground-based optical sensors for decades (Jonckheere et al., 2004). Several biological and physical processes are related to the total plant surface, particularly photosynthesis, respiration, transpiration, carbon and nutrient cycles, and rainfall interception. Hemispherical photography is commonly used to retrieve PAI and uses the contrast between canopy components and sky as a way to measure gap fraction. Similarly, the LAI-2000/2200 instrument (Li-Cor, Inc., Lincoln, NE) calculates transmittance based on the ratio between above and below canopy light intensity. Terrestrial LIDAR offers an alternative to these passive sensors for deriving gap probability and PAI. TLS effectively measures canopy gaps (size and location) directly, and is not dependent on indirect (solar) illumination, which can create uncertainty in estimates based on passive sensing approaches. In addition to the added certainty in PAI estimates, terrestrial LIDAR can be used to derive vertical plant profiles that describe the plant area volume density (PAVD) as a function of canopy height. These vertical plant profiles enable monitoring of forest structure not only as a function of time, but also as a function of canopy height, which can be important for characterizing disturbance, recovery and natural successional changes. Vertical plant profiles can also be used to derive various metrics such as canopy base height, tree height or height of maximum density of the canopy (Calders et al., 2015b, 2014, Ni-Meister et al., 2010, Jupp et al., 2009), which can be used in isometric and allometric equations to derive timber volume and above-ground biomass (AGB). Additionally, these direct measures of forest canopy vertical structure have important applications for characterizing tropical forest types and successional stages (Cuni-Sanchez et al., 2015).

In parallel to the development of gap probability methods for quantifying forest structure, methods have also been developed to estimate more familiar forest monitoring properties such as diameter at breast height (DBH), tree height and AGB directly from the 3D point cloud. DBH and tree height are important structural measures that are historically used to predict AGB based on empirical allometric relationships (Chave et al., 2014, 2004). Numerous studies have estimated DBH using least square fitting. Tansey et al. (2009) reported a root mean squared error (RMSE) of 0.019 to 0.037m and analysis in Calders et al. (2015a) showed an RMSE of 0.0239 m. Tree height estimates in the earlier days of terrestrial LIDAR reported large errors (RMSE 1.4 to 4.4 m) (van Leeuwen and Nieuwenhuis, 2010). Calders et al. (2015a) have shown that tree height estimates from TLS data captured with the RIEGL VZ-400 agreed closely (RMSE 0.55 m) with destructive harvest measurements, and showed closer agreement and less bias than traditional height measurements (RMSE 1.28 m).

The combination of multiple individual scans using registration targets significantly reduces occlusion. Several reconstruction algorithms have been developed to exploit these TLS point clouds generated from multiple co-registered scans, to produce full 3D reconstructions of tree structure. These so-called Quantitative Structural Models (QSMs) provide topologically-connected estimates of tree trunks and branches down to fine (cm) scale, allowing for straightforward calculation of volume. Combined with estimates of basic wood density, these volumes allow straightforward calculation of above-ground woody biomass, a critical parameter for monitoring forest carbon stocks and fluxes. Dassot et al. (2012) used simple geometric fitting to model the woody structure of individual trees, whereas Hosoi et al. (2013) used a voxel-based approach. Both these approaches require a substantial amount of manual input. Côté et al. (2011, 2009) developed an automated algorithm that models a free form circular cross-section woody model based on intensity filtering of the LIDAR returns. Fine branching and leaves are added to the woody structure based on the low intensity returns. All these methods suffer from the difficulty of assessing the accuracy of the resulting reconstructed QSMs. Disney et al. (2012) developed a 3D modelling approach to overcome this, by using 3D simulated TLS data from tree models whose structure and volume is known *a priori*. This approach was applied by Raumonen et al. (2013), who describe a reconstruction method based on local patch fitting to produce cylinder-based QSMs. Volume estimates of QSM and basic density were compared to destructively harvested measures of AGB, showing an overestimation of less than 10% compared to a 30% underestimation when traditional allometric equations were used (Calders et al., 2015a). Hackenberg et al. (2015) developed a slightly different approach to QSM reconstruction, but found similar results when comparing TLS derived AGB estimates through cylinder fitting against destructively harvested measures, with prediction errors ranging from 2.75% to 7.30%. The AGB of the single trees used in both studies was relatively small (Hackenberg et al. (2015) < 0.7 t, Calders et al. (2015a) < 3.4 t) compared to tropical trees, which can exceed an AGB of 75 t (Chave et al, 2014). Testing of these methods in more challenging and complex biomes, such as tropical rainforests, are essential if TLS derived AGB estimates are to be accepted in international reporting, such as through the REDD+ framework.

2.10.3.3 Status and outlook

There has been substantial progress in the development and validation of terrestrial LIDAR methods to support forest inventory. More practical methods of acquiring and processing TLS data are needed to facilitate more widespread use of TLS, in particular for Measurement, Reporting and Verification (MRV) systems for national forest inventories and international treaties such as REDD+. However, challenges and trade-offs still remain regarding measurement efficiency, measurement detail and accuracy, and the availability of software to implement gap fraction and geometric modelling methods. Terrestrial LIDAR has developed to the point where it can be used as a rapid and robust tool for forest measures that are related to gap probability estimates, and estimates of forest monitoring properties have been shown to be higher-accuracy than traditional survey methods, particularly tree height. However, the relationship between gap probability and significant structural metrics is empirical and not well understood. Current geometric modeling methods provide clear, detailed and accurate characterization of structure on an individual tree level, but more development is required to automate algorithms to provide efficient plot level based estimates.

The quality of TLS data and the types of sensors will increase rapidly over the next decade. This will present challenges in exploiting these developments, including understanding the impact of sensor specifications on the derived forest metrics (Armston et al., 2014). However, an increased availability of data will also enable the comparison of similar forest structure in different biomes in an objective and quantitative way, and to monitor the change in structure over time. In addition, more data and instruments is likely to drive effort devoted to processing and testing methods. Studies estimating AGB from TLS are encouraging as TLS does not only support near-direct estimates of AGB (via volume, and wood density), but can also improve current allometric equations. Destructively harvested reference measures of volume and AGB are expensive and time-consuming and hence tend to be very limited both in terms of the number of trees and their size (very few large trees are sampled in this way). TLS data have the potential to provide similar volume information at a fraction of the cost, and unbiased in terms of tree size distribution. This is likely to reduce the uncertainty of the resulting AGB values compared with allometric methods that underpin all current field-based and satellite-derived AGB estimates.

The Salford Advanced Laser Canopy Analyser (SALCA; Danson et al., 2014, Gaulton et al., 2013) and the successor of the EVI, the Dual-Wavelength Echidna Lidar (DWEL; Douglas et al., 2012) are two recently developed terrestrial LIDAR systems for measuring vegetation structure. Both these systems use dual-wavelengths to allow separation of moist photosynthetic components from dry, non-photosynthetic components within a given point cloud. The objective is to further improve both estimates of leaf area distributions and woody structure. It is important to acknowledge that these instruments are not yet ready for operational deployment in large-scale fieldwork campaigns. It should be noted that these instruments have also been developed to estimate average canopy properties over the hemispherical region above a specific scan location, rather than in discrete angular directions, unlike the commercial instruments which have typically been developed with angular precision in mind due to their intended application in high resolution surveying. Low-cost, light-weight and portable time-of-flight TLS instruments have been developed (Schaaf et al., 2014, Bauwens et al., 2014) and have been used to derive forest structure in tropical rainforests and mangroves. The maximum range, angular resolution or accuracy is lower than some commercial sensors, but customized sampling designs may mitigate the impacts of their limitations and these research instruments provide a catalyst for commercial instrument (and software) development specifically targeting vegetation structural assessment in the future.

2.10.3.4 Acknowledgements

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2.10.3.5 References

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2.10.4 Forest monitoring using Synthetic Aperture Radar (SAR) observations

2.10.4.1 Synthetic Aperture Radar technology

Synthetic Aperture Radar (SAR) sensors have been used since the 1960s to produce remote sensing images of earth-surface features based on the principals of radar (radio detection and ranging) reflectivity. Over the past two decades, the science and technology underpinning radar remote sensing has matured considerably. Additionally, high-resolution global digital elevation models (e.g., from the 2000 Shuttle Radar Topography Mission, SRTM), which are required for accurate radar calibration and image geolocation, are now freely available. Together, these advancements have enabled and encouraged the development and operational deployment of advanced space-borne instruments that now make systematic, repetitive, and consistent SAR observations of tropical forest cover possible at regional to global scales.

Radar remote sensors complement optical remote sensors in two fundamental ways. First, whereas optical sensors passively record electromagnetic energy (e.g., sun light) radiated or reflected by earth-surface features, radar is an active system, meaning it serves as the source of its own electromagnetic energy. As a radar sensor orbits the Earth, it transmits short pulses of energy toward the surface below, which interact with surface features such as forest vegetation. The portion of this energy that is reflected back toward the sensor - backscattered - is recorded. Second, while optical sensors operate primarily in the visible and infrared (ca. 0.4-15.0 μm) portions of the electromagnetic spectrum, radar sensors operate in the microwave region (ca. 3-70 cm). Whereas the short electromagnetic waves in the visible and infrared range are readily scattered by atmospheric particulates (e.g., haze, smoke, and clouds), the microwave signals generally penetrate through them, making radar remote sensing an invaluable tool for imaging tropical forests which are commonly covered by clouds. Moreover, microwaves penetrate into forest canopies, with the amount of backscattered energy dependant in part on the three-dimensional structure and moisture content of the constituent leaves, branches and stems, and underlying soils, thus resulting in useful information on forest structural attributes including structural forest cover type and aboveground biomass. Thereby, the degree to which microwave energy penetrates into forest canopies depends on the frequency/wavelength of the electromagnetic waves. Generally speaking, incoming microwaves are scattered most strongly by surface elements (e.g., leaves, branches, and stems) that are large relative to the wavelength. Hence, longer wavelengths (e.g., P-/L-band) penetrate deeper into forest canopies than shorter wavelengths (e.g., C-/X-band).

The practical use of SAR for forest monitoring has followed developments in the technology and observation capability. The Brazilian RADAMBRASIL project in 1970 was the first to provide a baseline of the extent of forest cover in the Brazilian Amazon without inference from cloud or smoke haze. Focusing on a large number of study areas around the Earth, the Shuttle imaging Radar (SIR-A, SIR-B) and SIR-C/X-SAR missions (X-, C- and L-band) in the early 1990's allowed researchers to identify the benefits of using different radar wavelengths and polarizations for detecting forest extent, characterising areas cleared of forest, and retrieving forest biomass and structural attributes (e.g., Kellndorfer *et al*., 1998). The capacity of interferometric SAR for retrieving forest height across larger areas was demonstrated using SRTM data (Kellndorfer *et al*., 2004). The Japanese JERS-1 SAR mission provided the first consistent pan-tropical and pan-boreal observations, and the long wavelength L-band SAR data proved useful for the classification of forest/non-forest areas and identification of secondary growth, particularly when time-series data were used. The L-band data also facilitated temporal mapping of standing water below closed-canopy forests, and hence differentiation of floodplain and swamp forests, and better understanding of the seasonal dynamics of inundation across large river catchments such as the Amazon and Congo (e.g., Hess *et al*., 1995).

In addition to wavelength, current and near-future SAR systems have multi-polarisation capacities which, provide additional thematic information and sensitivity with which to characterize forest structure. The first civilian space-borne SAR sensors are now also being operated at spatial resolutions finer than 5 meters (e.g., TerraSAR-X, COSMO-SkyMed), which is of great potential for example where the mapping of logging roads and associated forest degradation patterns is concerned. A listing of past, current, and future SAR sensors is included in Table 2.10.1.

Table 2.10.1. Summary of key past, current and planned space-borne Synthetic Aperture Radar (SAR) sensors and their characteristics.

Satellites/ sensors	**Country**	**Period of Operation**	**Band**	**Wave-length (cm)**	**Polarisation**	**Spatial Resolution (m)**	**Orbital Repeat (days)**
ERS-1	Europe	1991-2000	C	5.6	Single (VV)	26	3-176
JERS-1	Japan	1992-1998	L	23.5	Single (HH)	18	44
ERS-2	Europe	1995-2011	C	5.6	Single (VV)	26	35
RADARSAT 1	Canada	1995-2013	C	5.6	Single (HH)	8-100	3-24
ENVISAT/ ASAR	Europe	2002-2012	C	5.6	Single, Dual	30-1000	35
ALOS/ PALSAR	Japan	2006-2011	L	23.6	Single, Dual, Quad	10-100	46
RADARSAT 2	Canada	2007-	C	5.6	Single, Dual, Quad	3-100	24
TerraSAR-X TanDEM-X	Germany	2007- 2010-	X	3.1	Single, Dual, Interferometric	1-16	11
COSMO-SkyMed	Italy	2007-	X	3.1	Single, Dual	1-100	16
RISAT-1	India	2012-	C	5.6	Single, Dual, Quad	1-50	25
ALOS-2/ PALSAR-2	Japan	2014-	L	23.8	Single, Dual, Quad	1-100	14
Sentinel-1A Sentinel-1B	Europe	2014- Scheduled 2016	C	5.6	Single, Dual, Quad	9-15	12
SAOCOM-1A SAOCOM-1B	Argentina Italy	Scheduled 2015, 2016	L	23.5	Single, Dual, Quad	10-100	16
NovaSAR	U.K.	Scheduled 2015	S	9.4	Single, Dual, Triple, Quad	6-30	14
RADARSAT Constellation 1/2/3	Canada	Scheduled 2018	C	5.6	Single, Dual, Quad	1-100	12
BIOMASS	Europe	Scheduled 2020	P	69.0	Quad	50	Varying

Direct estimation of above-ground biomass from SAR data has been largely based upon the variable backscatter response from the density of canopy elements, and hence biomass. It has been particularly successful in estimating above ground biomass of lower-biomass forests using both P- and L-band wavelengths. In addition to backscatter, measures of image texture have also been shown to correlate strongly with variation in biomass between different locations as texture contains information on the structural and geometrical properties of forest canopies. However, the use of SAR data for directly estimating biomass has well known limitations, including the saturation of backscatter response at medium to high biomass levels, and so may be unsuitable for estimating biomass in many types of forest. Several studies have reported saturation of SAR backscatter at aboveground forest biomass of 10-20 t/ha for C-band and 60-100 t/ha for L-band (primarily at HV polarisation). While the use of backscatter ratios or data acquired under relatively dry surface moisture conditions may extend these ranges

(Lucas *et al*., 2010), this remains a limitation on the operational use of SAR backscatter for estimating forest biomass in medium-high biomass regions. Significant potential exists for retrieving biomass at higher levels with the planned launch of the P-band BIOMASS mission in 2020, although the combination of higher frequency SAR data may be needed for low biomass forests because of reduced interaction with trees of smaller size. The integration of radar with optical or LIDAR sensors (e.g., Landsat or ICESAT) may also be useful for refining estimates of above-ground biomass, although techniques are still exploratory.

For operational forest and land cover monitoring over national scales to be realised requires availability of spatially and temporally consistent time-series of satellite data, both optical and radar. Amongst optical missions, Landsat-7 was the first medium-resolution satellite to feature a truly global-scale long-term acquisition plan with the aim to systematically cover all global land areas on a repetitive basis. The Landsat Long-Term Acquisition Plan (LTAP) has been in operation since 1999 and is now is being implemented also for Landsat-8 (Fosnight *et al.*, 2011). The first radar-based systematic observation strategy dates back to experiences gained with the JERS-1 SAR which, during the last three years of its lifetime (1995-1998), was used to acquire cloud-free data in a consistent manner over the entire tropical and boreal zones of the Earth (Rosenqvist *et al.,* 2000), demonstrating the utility and feasibility of acquiring medium spatial resolution (18 m) data systematically and repetitively at continental scales. The global acquisition strategy concept was implemented, in full, for L-band SAR (PALSAR) on-board the ALOS-1/-2 satellites, which was programmed to acquire one coverage at 10 and 20 metre resolution of all land areas every six months during its lifetime (Rosenqvist *et al.,* 2007). The extent of the effort is illustrated in Figure 2.10.1., which shows a 25 metre resolution mosaic consisting of about 70,000 PALSAR scenes, with about 95% of the data acquired within a 4-month period. Such mosaics have been generated for each of the years 2007-2010 (Shimada, M. *et al*. 2013). The ALOS acquisition strategy also comprised bi-monthly observations at lower resolution (100 m) over the pan-tropical belt and over wetlands of global significance identified by the Ramsar Convention on Wetlands. While the ALOS mission ended in 2011, the global wall-to-wall acquisitions were resumed in 2014 through Japan's ALOS-2 mission, which features a similar global acquisition strategy and an enhanced radar sensor.

The importance of systematic acquisition strategies is now becoming acknowledged by several other space agencies and a number of near-future SAR missions beyond ALOS-2 are also in the process of implementing such global observation plans. This includes the European Sentinel-1A/1B and the Argentinean SAOCOM-1A/1B missions, which both will provide systematic forest observations from 2014 and onwards. A joint effort to establish a coordinated global multi-mission acquisition strategy for both optical and SAR satellites was initiated by the Committee on Earth Observation Satellites (CEOS) in 2012, undertaken by a number of national space agencies within the framework of the Global Forest Observation Initiative (GFOI) in support to countries implementing REDD+ (CEOS SDCG, 2013).

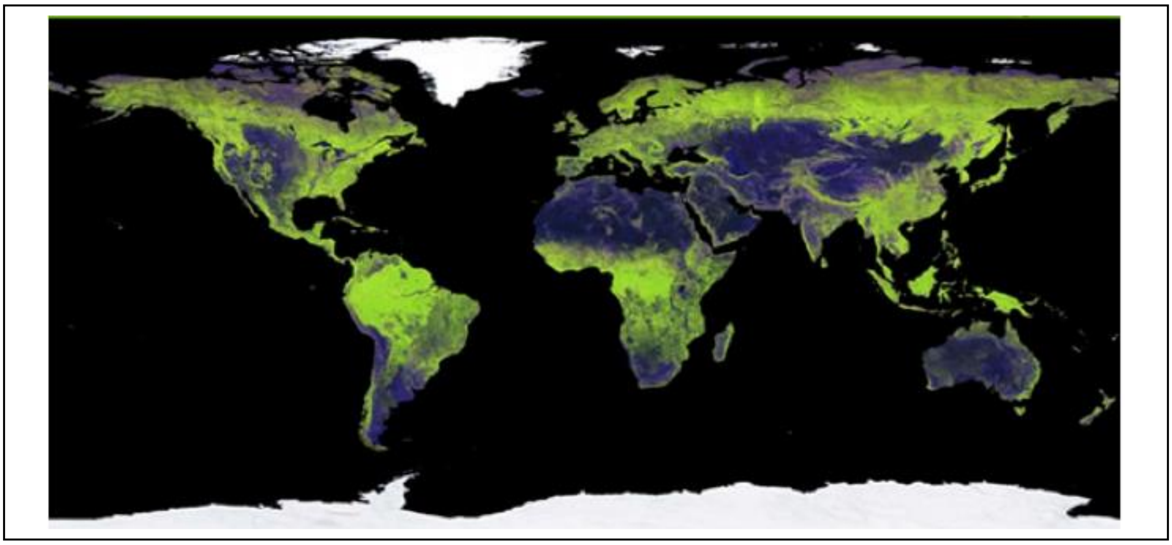


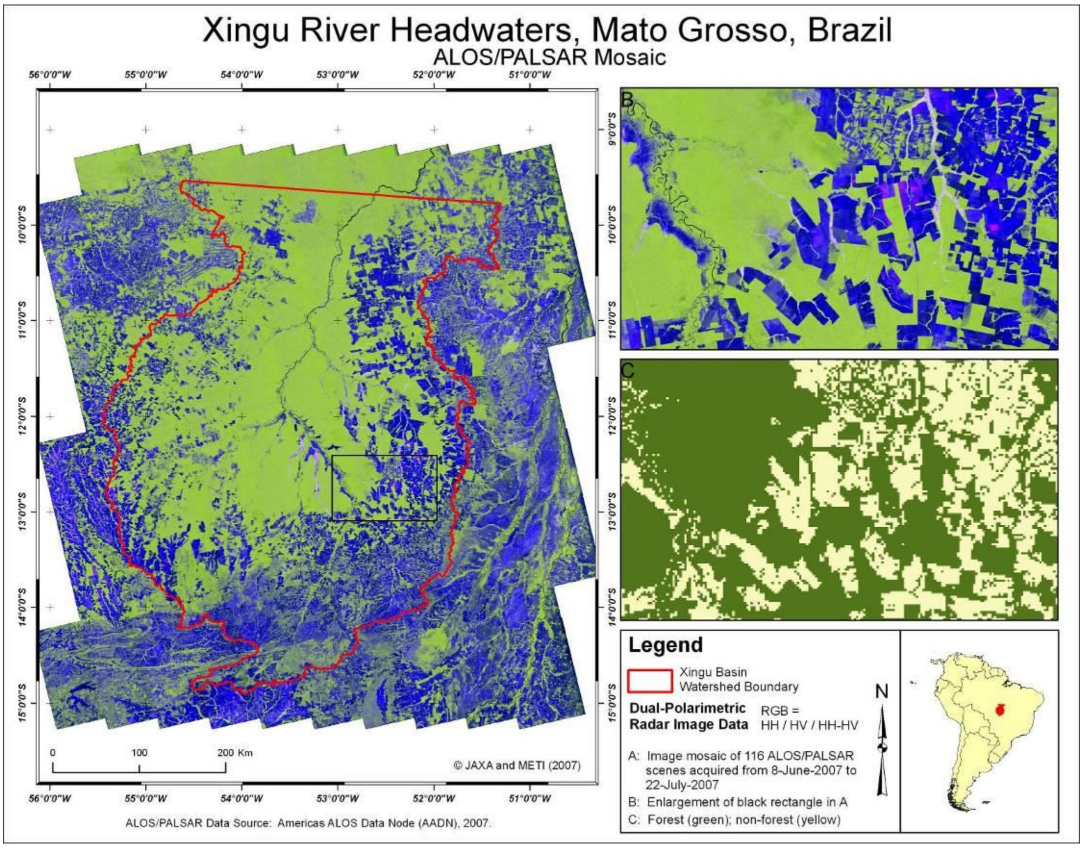
Figure 2.10.1. A world without clouds. Global ALOS PALSAR colour composite mosaic at 25 m pixel spacing (R:HH, G:HV, B:HH/HV) consisting of approximately 70,000 scenes. 95% of the data were acquired within the time period June-October 2009. Such mosaics have been generated also for the years 2007, 2008 and 2010 (Shimada, M. *et al*. 2013).

2.10.4.2 Case Study: Xingu River Headwaters, Mato Grosso, Brazil

Given the excellent positional accuracy (~9.3 m) of ALOS PALSAR data and the recent availability of advanced radar image processing methods, regional- to continental-scale image mosaics can be readily produced for any location that has been systematically imaged by the ALOS PALSAR sensor. Figure 2.10.2 shows a large-area (ca. 400,000 km2) image mosaic of ALOS PALSAR data, which covers the headwaters of the Xingu River, in Mato Grosso, Brazil. Data were acquired between June 8th and July 27th, 2007, as part of a 4-month global acquisition (see Figure 2.10.2). This particular mosaic was generated in less than one week using two distinct (i.e., dual-polarimetric) PALSAR information channels: 1) image data derived from microwave energy that was both transmitted and received by the PALSAR antenna in the horizontal direction (i.e. parallel to Earth’s surface), and b) image data derived from microwave energy transmitted in the horizontal direction, but received in the vertical direction (i.e., perpendicular to the Earth’s surface). The former case is referred to as HH-polarisation while the latter case is referred to as HV-polarisation. The concept of polarisation is an important aspect of radar remote sensing because earth-surface features such as forest canopies respond differently to different polarisations.

Because radar sensors are active remote sensing systems (i.e., they transmit and receive their own microwave energy, and thus complement passive optical sensors which measure reflected sun light), radar images are always visual representations (i.e., displayed in the visible spectrum) of microwave energy received at and recorded by the sensor. Single radar information channels are typically displayed as gray scale images. When interpreting a radar image it is a general rule of thumb that increasing brightness corresponds to a greater amount of energy recorded by the sensor. Applying this rule of thumb to the interpretation of vegetated regions in an ALOS PALSAR image, areas with a greater amount of vegetation biomass of a given structural type will appear brighter due to the greater amount of energy scattered back to and recorded by the sensor. If multiple radar information channels (i.e., multiple polarisations) are available, colour images can be generated by assigning specific channels or combinations of channels to each of the visible red, green, and blue (RGB) channels commonly used for display in computer monitors. To create the colour (RGB) image displayed in Figure 2.10.2, the HH channel was assigned the colour red, the HV channel was assigned the colour green, and the difference between the two (HH minus HV) was assigned the colour blue. Hence, green and yellow image tones correspond to instances where both HH and HV information channels have high energy returns (e.g., over forested and urban areas). Blue and magenta tones are generally found in non-forested (e.g., agricultural) areas where HH-polarized energy tends to exhibit higher returns from the surface than does HV-polarized energy. The information contained in the three ALOS PALSAR image channels has recently been used to demonstrate the utility of these data for accurate large-area, forest/non-forest mapping. Ground validation in this area demonstrated that an overall classification accuracy of greater than 90% was achieved from the ALOS radar imagery.

Figure 2.10.2. Xingu River headwaters, Mato Grasso, Brazil. The radar image mosaic is a composite of 116 individual scenes (400,000 km^2) acquired by the PALSAR sensor carried on board ALOS. A preliminary land cover classification has been generated with an emphasis on producing an accurate forest/non-forest map. In the forested areas, the sensitivity of the PALSAR data to differences in aboveground biomass is also being investigated in collaboration with the Amazon Institute of Environmental Research (IPAM). Data by JAXA/METI and American ALOS Data Node. Image processing and analysis by The Woods Hole Research Center, 2007.

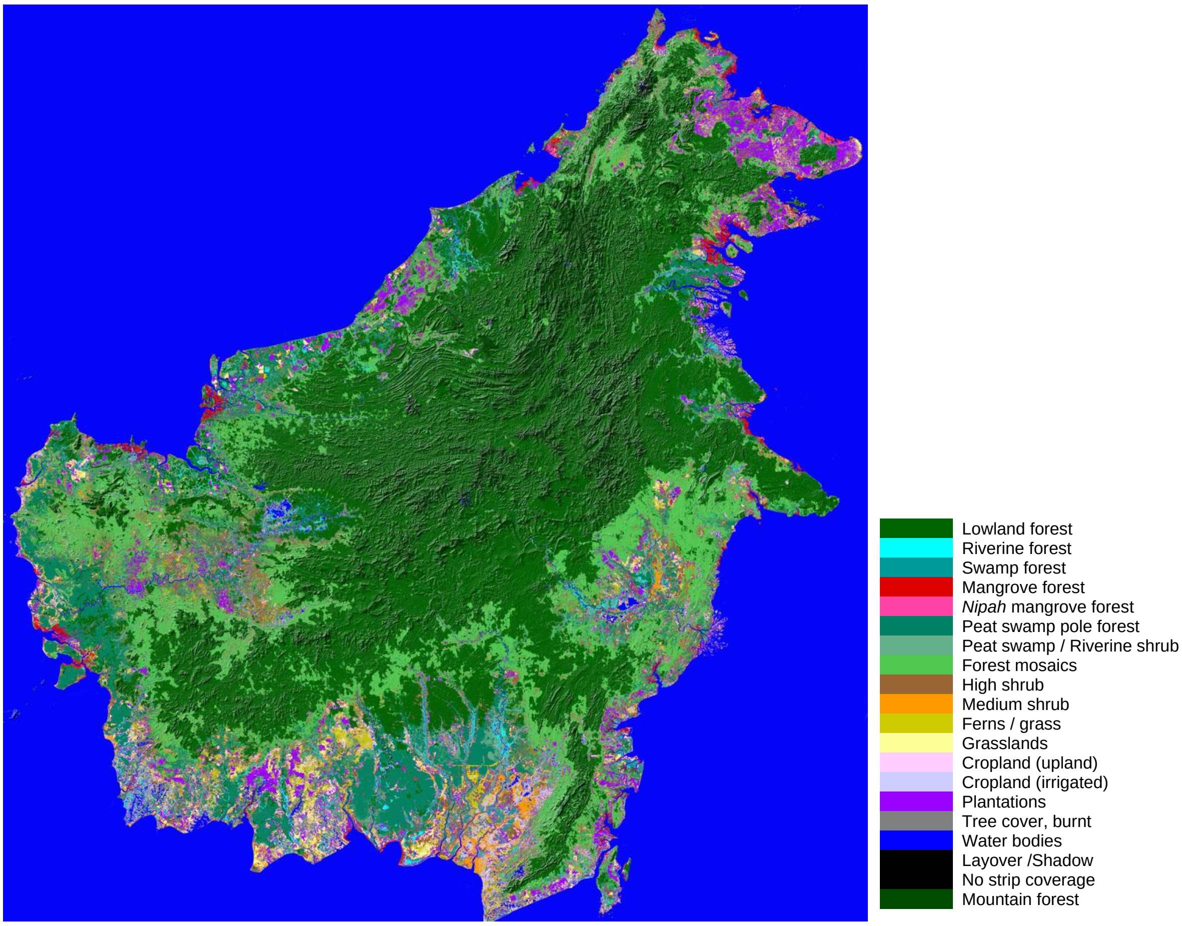


2.10.4.3 Case Study: Wide area land cover mapping of Borneo

One of the main prototype areas for demonstrating PALSAR's wide-area forest and land cover mapping methodology is the island of Borneo in South East Asia. Borneo is the third largest island in the world and covers approximately 750,000 km^2. Almost three quarters of the island is part of Indonesia (Kalimantan), while other parts are covered by Malaysia (Sarawak and Sabah) and the sultanate of Brunei Darussalam. Borneo was almost entirely covered by tropical evergreen broadleaved forest until the 1950s. Intensive logging of predominantly commercial dipterocarp species and conversion to cropland, oil palm and timber plantations has reduced forest cover significantly. Other major natural vegetation types include: peat swamp forests, which are found in the coastal and sub-coastal lowlands of Borneo, freshwater swamps along rivers inland, and mangrove forests in the coastal plains along the coastlines.

This example is the first of its kind and shows a forest and land cover map based on a dual-season classification of Fine Beam Single (FBS) and Fine Beam Dual (FBD) polarisation (path) image pairs of the year 2007. To cover Borneo the equivalent of 554 standard images is required. The map features 18 land cover classes. Qualitative and quantitative validation results and findings have been undertaken and the accuracy achieved is widely considered adequate, a very promising result for a sub-continental high resolution (50 m) map based on just single-year radar data. This work was undertaken as part of the ALOS Kyoto & Carbon Initiative (JAXA EORC, 2013).

Figure 2.10.3. Land cover map of Borneo island, derived from dual-season L-band SAR (ALOS PALSAR) data from 2007 (Hoekman *et al.*, 2010)

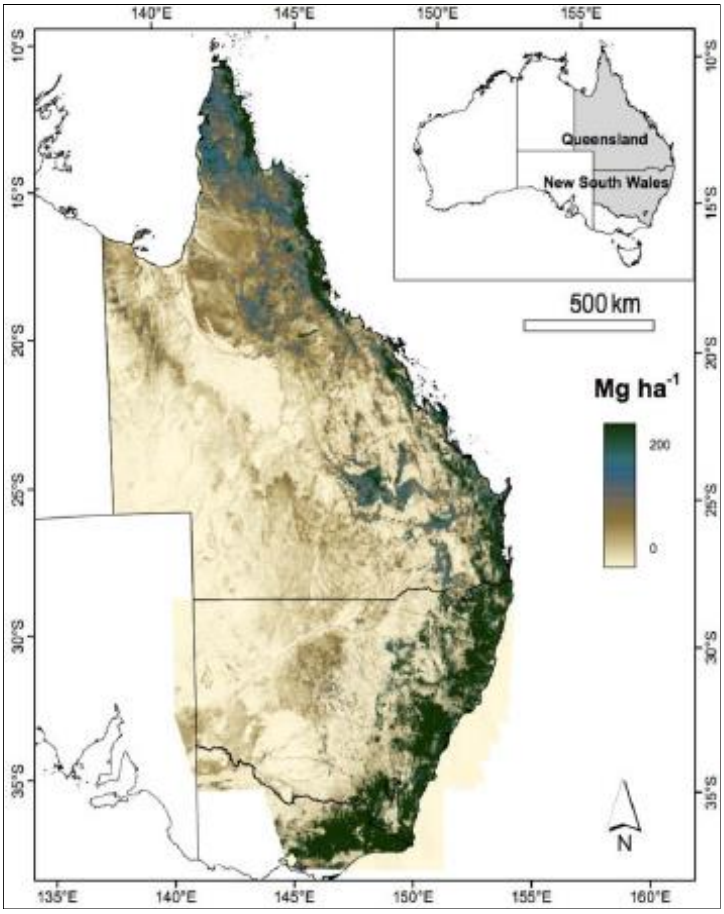


2.10.4.4 Case Study: Forest characterization in Eastern Australia.

The three-dimensional structure (e.g. height) and biomass of woodlands can be approximated using longer wavelength Synthetic Aperture Radar (SAR). For estimating above-ground biomass (ABG), many studies worldwide have utilised L-band SAR data but have been limited by saturation of the backscatter and no algorithm has provided consistent retrieval between scenes and over time. This is partly because of differences in the structure of the vegetation types observed but also variability in environmental (freeze/thaw, wet/dry) conditions occurring at the time of the satellite overpass. However, Lucas et al. (2010) established for eastern Australia, that AGB retrieval could be optimised using ALOS PALSAR data acquired under conditions of minimal surface moisture, particularly in open forests and woodlands where greater interaction with the ground surface occurs. Attention to surface conditions was found also to be essential as the differences resulting may be of similar magnitude to those observed as a consequence of actual changes in vegetation amount. Using ALOS PALSAR data acquired under dry conditions in 2009, a preliminary map of AGB was generated for Queensland and New South Wales in Australia using an empirical relationship established between the L-band HV backscatter data and field-based estimates of biomass. By minimising the impact of surface moisture in the SAR imagery by careful scene selection, the ABG sensitivity range could be improved beyond 100 t/ha (Figure 2.10.4).

Characterisation of forests can also be improved through integration of data from optical sensors. For example, by using the combination of Landsat-derived Foliage Projective Cover (FPC) with ALOS PALSAR HH and HV data, early regrowth forests in Australia with a high level of cover and low amount of woody material (and hence LOWER backscatter response at L-band) have been distinguished from more advanced stages of regrowth. Similarly, differences in FPC and both L-band HH and HV backscatter relative to that of forests known to be undisturbed have been used to indicate different levels of maturity or disturbance. These forest growth classes can then in turn be associated with different levels of AGB.

Figure 2.10.4. Above-ground biomass map over Eastern Australia, 2009, derived from L-band SAR (ALOS PALSAR) data acquired under minimum surface moisture conditions (Lucas *et al.*, 2010).



2.10.5 Integration of satellite and in situ data for biomass mapping

The advantage of biomass estimation approaches that incorporate some form of remotely sensed data is through provision of a synoptic view of the area of interest, thereby capturing the spatial variability in the attributes of interest (e.g., height, crown closure). The spatial coverage of large area biomass estimates that are constrained by the limited spatial extent of forest inventories may be expanded through the use of remotely sensed data. Similarly, remotely sensed data can be used to fill spatial, attributional, and temporal gaps in forest inventory data, thereby augmenting and enhancing estimates of forest biomass and carbon stocks derived from forest inventory data. Such a hybrid approach is particularly relevant for non-merchantable forests where basic inventory data required for biomass estimation are lacking. Minimum mapping units are a function of the imagery upon which biomass estimates are made. Further, costs will be a function of the imagery desired, the areal coverage required, the sophistication of the processing, and needs for new plot data. For confidence in the outcomes of biomass estimation and mapping from remotely sensed data some form of ground calibration / validation data is required (Goetz et al., 2009).

Biomass estimates may range from local to global scales, and for some regions, particularly tropical forest regions, there are large variations in the estimates reported in the literature. Global and national estimates of forest above-ground biomass are often non-spatial estimates, compiled through the tabular generalization of national level forest inventory data. Due to the importance for reporting and modelling, a wide-range of methods and data sources for generating spatially explicit large-area biomass estimates have been the subject of extensive research.

A variety of approaches and data sources have been used to estimate forest above ground biomass (AGB). Biomass estimation is typically generated from: (i) field measurement; (ii) remotely sensed data; or (iii) ancillary data used in GIS-based modelling. Estimation from field measurements may entail destructive sampling or direct measurement and the application of allometric equations. Allometric models are constructed from a measured sample of biomass as the dependent variable and tree variables that are easy to measure in the field such as diameter, height, and species. Although the models may be species- or site-specific, they are often generalized to represent mixed forest conditions or large spatial areas. Biomass is commonly estimated by applying conversion factors (biomass expansion factors) to tree volume (either derived from field plot measures or forest inventory data) or applying allometric regression models to forest stand tables (tables of number of trees per diameter class; cf. section 2.2). Although allometric model predictions are often used as if they are observations without error, in fact they are subject to multiple sources of uncertainty including model parameter uncertainty, model residual variability, measurement error in the predictor variables, and uncertainty in volume to biomass and biomass to carbon conversion factors. As per multiple recent studies, the effects of these sources of uncertainty on large area biomass and carbon estimates should not necessarily be considered negligible (Ståhl et al., 2014; McRoberts et al., 2015; Chen et al., 2016). In particular, McRoberts et al. (2016) showed that the effects of using continental versus local models induced deviations in large area estimates as great as 20% uncertainty and use of a pan-species wood density estimate increased uncertainty by as much as 40%, even for local models. Relationships between biomass and other inventory attributes (e.g., basal area) have also been reported. The use of existing forest inventory data to map large area tree AGB has been explored; conversion tables were developed to estimate biomass from attributes contained in polygon-based forest inventory data, including species composition, crown density, and dominant tree height.

Remotely sensed data have become an important data source for biomass estimation. Generally, biomass is either estimated via a direct relationship between spectral response (or backscatter in the case of SAR) and biomass using multiple regression analysis, k-nearest neighbor, neural networks, statistical ensemble methods (e.g.

decision trees), or through indirect relationships, whereby attributes estimated from the remotely sensed data, such as leaf area index (LAI), structure (crown closure and height) or shadow fraction are used in equations to estimate biomass. When using remotely sensed data for biomass estimation, the choice of method often depends on the required level of precision and the availability of plot data. Some methods, such as k-nearest neighbor require representative image-specific plot data, whereas other methods are more appropriate when scene-specific plot data are limited.

A variety of remotely sensed data sources continue to be employed for biomass mapping including coarse spatial resolution data such as SPOT-VEGETATION, AVHRR, and MODIS. To facilitate the linkage of detailed ground measurements to coarse spatial resolution remotely sensed data (e.g., MODIS, AVHRR, IRS-WiFS), several studies have integrated multi-scale imagery into their biomass estimation methodology and incorporated moderate spatial resolution imagery (e.g., Landsat, ASTER) as an intermediary data source between the field data and coarser imagery. Research has demonstrated that it is more effective to generate relationships between field measures and moderate spatial resolution remotely sensed data (e.g., Landsat), and then extrapolate these relationships over larger areas using comparable spectral properties from coarser spatial resolution imagery (e.g., MODIS). Following this approach alleviates the difficulty in linking field measures directly to coarser spatial resolution data, although a number of other techniques have been devised (see background readings).

Landsat TM and ETM+ data are the most widely used sources of remotely sensed imagery for forest biomass estimation. Numerous studies have generated stand attributes from LIDAR data, and then used these attributes as input for allometric biomass equations. Other studies have explored the integration of multispectral, LIDAR and RADAR data for biomass estimation, often using a combination of spectral response, image texture and backscatter as additional variables in multivariate regression models.

GIS-based modelling using ancillary data exclusively, such as climate normals, precipitation data, topography, and vegetation zones is another approach to biomass estimation. Some studies have also used geostatistical approaches (i.e., kriging) to generate spatially explicit maps of AGB from field plots, or to improve upon existing biomass estimation. More commonly, GIS is used as the mechanism for integrating multiple data sources for biomass estimation (e.g., forest inventory and remotely sensed data). For example, MODIS, JERS-1 SAR, QuickSCAT, SRTM, climate and vegetation data have been combined to model forest AGB in the Amazon Basin.

A key challenge in the use of remotely sensed data to estimate forest biomass is the lack of consistency in results derived from different sensors and methods, and the applicability of relationships observed across different scales with respect to both time and space. This extends right through the remote sensing system, with variability in the resolutions and calibration of sensors, to uncertainty in image pre-processing procedures to relationships observed between remotely sensed data and biomass, and the procedures for scaling-up biomass estimates. Added to uncertainty in biomass estimation from ground-based methods, there is a requirement for research to understand sources of uncertainty and develop a suite of robust and reliable remote sensing methods that are equally applicable across time and space.

2.10.6 Targeted airborne surveys to support carbon stock estimations – a case study

Ground based methods for estimating biomass carbon of the tree component of forests are typically based on measurements of individual trees in many plots combined with allometric equations that relate biomass as a function of a single dimension, e.g., diameter at breast height (dbh), or a combination of dimensions, such as dbh and height. A potential way of reducing costs of measuring and monitoring the carbon stocks of forests is to collect the key data remotely, particularly over large and often difficult terrain where the ability to implement an on-the-ground statistical sampling design can be difficult.

There are limitations of remotely sensed products to measure simultaneously the two key parameters for estimating forest biomass from above (i.e., tree height and tree crown area). However, positive experiences exist with systems using multispectral three-dimensional aerial digital imagery that usually fits on board a single-engine plane. Such systems collect high-resolution overlapping stereo images from a high-definition video camera (≤ 10 cm pixel size). Spacing camera exposures for 70–80 % overlap provides the stereo coverage of the ground while the profiling laser, inertial measurement unit, and GPS provide georeferencing information to compile the imagery bundle-adjusted blocks in a common three-dimensional space of geographic coordinates. The system also includes a profiling laser to record ground and canopy elevations. The imagery allows distinguishing individual trees, identifying their plant type and measuring their height and crown area. The measurements can be used to derive estimates of aboveground tree biomass carbon for a given class of individuals using allometric equations (e.g. between crown area and biomass). Biomass can be measured in the same way as in ground plots, to achieve potentially the same accuracy and precision, but with potentially less investment in resources. In addition, the data can be archived so that, if needed, the data could be re-evaluated or used for some future purpose.

As an example, the 3 D digital imagery system has been tested in highly heterogeneous pine savanna (Brown et al, 2005) and a closed broadleaf forest (Pearson et al., 2005), both in Belize. In the pine savanna, the extreme heterogeneity creates the requirement for high intensity sampling and consequently very high on the ground measurement costs. For the imagery system, the highest costs are fixed and the cost of analyzing high numbers of plots is low in comparison to measurements on the ground (Brown et al., 2005). The study of the closed tropical forest shows that its complex canopy is well suited to the 3D imagery system. The complex multi-layered canopy facilitates the identification and measurement of separate tree crowns. The studied area is particularly suited due to its flat topography. In the closed forest it was often complex to measure ground height adjacent to each tree, if topography were varied it would be necessary to use an alternate equation that does not employ tree height and would therefore be less precise.

Table 2.10.2. Results from case studies using the 3D digital imagery system for estimating carbon stocks of two forest types in Belize.

Forest type	Number of imagery plots	Estimated carbon stock t C/ha	95% Confidence interval % of the mean	Reference
Closed tropical forest	39	117	7.4	Pearson et al. (2005)
Pine Savannah	77	13.1	16.8	Brown et al. (2005)

Imagery data are collected over the forest of interest by flying parallel transects. Once the imagery are processed, individual 3D image pairs are systematically selected and nested image plots (varying radii to account for the distribution of small to large crowned trees) are placed on the imagery and trees crown and height measurements taken (system uses ERDAS and Stereo Analyst). To convert the measurements from the imagery to estimates of biomass carbon, a series of allometric equations between tree or shrub biomass carbon were developed. The allometric equations resulting from this analysis were applied to crown area and vegetation height data obtained from the analysis of the imagery to estimate biomass carbon per plot and then extrapolated to per-hectare values (Table 2.10.2).

In terms of cost, an airplane, with aviation gas and pilot is needed to collect the imagery; experience has shown this to cost approximately US$ 300 per hour of engine time. Using a conventional field approach, the equivalent cost would be a vehicle rental for 20-50 day, the cost of which depends on local country conditions. In the Belize pine savanna study, it was found that the break-even point in person-hours was at 25 plots, where the conventional field approach was more time-efficient. However, as more than 200 plots would be needed in the pine savanna to achieve precision levels of less than 10% of the mean, the targeted airborne approach clearly has an advantage, even considering the different skill set needed by each approach. For the closed forest, just 39 plots were needed to estimate biomass carbon with 95 % confidence intervals equal to 7.4 % of the mean compared to the 101 ground plots that produced a comparable estimate with confidence intervals equal to 8.5 % of the mean.

2.10.7 Use of Unmanned Aerial Vehicles (drones) technology for local scale validation studies

2.10.7.1 Unmanned Aerial Vehicles (UAVs) technology

Unmanned aerial vehicles are commonly called as UAVs, UAS or drones. Historically the greatest uses of UAVs have been in the areas of intelligence surveillance and reconnaissance. However, recently, the use of UAVs are spreading rapidly in general public for lower survey cost than traditional platforms. For instance, UAVs are used in the real estate viewer, aerial photography, radiation monitoring, infrastructure monitoring, natural disaster monitoring, maritime monitoring, crop growth monitoring, policing and forest monitoring applications.

In general, UAVs in the private sector are categorized into two types based on an energy sources; a gasoline or a battery type. Furthermore, these two types are categorized into two types based on wing shape; multi-rotors or a fixed wing type. Over the past decades, a rotor wing type powered by gasoline source like a helicopter was the mainstream of UAVs. At present, multi-rotor wing type powered by a battery is becoming the mainstream. Because, in proportion to innovation in science and technology, devices in the UAVs components are improving miniaturization, high performance and weight saving, rapidly. Especially, a battery performance is remarkably improving and then flight time has been extended in comparison with the past one.

UAVs generally consist of 8 components; the main body, the rotor and wing, the energy source, the positioning system, the remote sensing sensors, the radio control system, the telemetry monitoring system and the flight control system. Recently, multi-rotor’s UAVs are becoming popular. The types of multi-rotor wing be classified into three models including 4 rotors, 6 rotors or 8 rotors, and each payload and flight time are different, respectively. Energy sources are gasoline and battery, and recent years, lithium-ion polymer battery called as Li-PO battery is becoming popular for UAVs due to high energy capacity and output. The positioning system consists of GPS, IMU and magnetometric sensor. Recently, UAVs have a dual channel GPS unit which can reduce positioning errors, has appeared in the market. Remote sensing sensors are camera, LIDAR, SAR, hyperspectral radiometer, dosimeter and so on. Every year, small and high specification sensors are appearing. Almost UAVs can carry out automatic flight based on the programmed flight course, as the flight control system. In many cases, an operator generates 3D flight plan using a map with DEM as the first step and installs the flight plan data into UAVs before actual flight as the second step. Specifically, flight vectors, altitude of flight vectors, orientation angle of UAVs, flight time, emergency action (GPS signal loss, low battery condition and radio control signal loss) are made a definition in a 3D flight plan.

UAVs in forest observation are expected at the point of view of the data cost, the spatial and vertical resolution and the temporal intervals against an airborne measurement. Airborne LIDAR data has become an important instrument for investigation of forest structure. Especially, LIDAR has the great potential for the generation of the DEM in comparison with other remote sensing instruments.

However, the airborne LIDAR has been often not suitable for the temporal studies to repeatedly measure forest status because of its data cost. Now, there are two ways to reconstruct 3D structure of objects in the engineering technology at the present. One method is using laser beam which can directly measure the position of the object, and the other method is using Photogrammetry based on computer vision technique. Applications using these methods and UAVs are beginning to implement into forest observation. Many researchers have shown the potential of the use of the UAV-borne LIDAR system and the UAV-borne camera system in order to reconstruct forest structures.

In case of the UAV-borne LIDAR system, Jaakkola et al. (2010) has shown that the hardware configuration of the custom integrated UAV LIDAR system, and the potential for individual tree mapping. Lin et al. (2011) have shown that the potential capability of fine scale mapping, in particular, the estimated individual tree height from point data of UAV and the simulated airborne point data was compared in the paper. In addition, Wallace et al. (2011, 2012) has shown that the error assessment at each scan angle and the effect of flight height. On the other hand, In case of UAV-borne camera system, HarDandois et al. (2013) has shown that the assessment of the accuracy and applicability of point clouds derived from multi-view stereoscopes based images from UAV for natural landscape mapping and monitoring. Point clouds generated from a lot of images using the Structure from Motion techniques (SfM). In this paper, the accuracy of the georeferencing point clouds derived from images which UAV took was 20-40 mm. In this case the distance was less than 50 m. Dandois et al. (2013) has shown that the potential for the generation of point clouds at different seasons (leaf on and leaf off) as the beginning of the Photogrammetry based on computer vision technique.

The way for 3D reconstruction of forest should be selected based on the requirement of accuracy.

2.10.7.2 For safe of UAVs observation

Recent years, since the price of UAVs is becoming low, there are many chances to purchase UAVs instead of remote sensing data. The safety and optimum operation of UAVs are needed and this point is quite different from traditional remote sensing research. Specifically, an operator has to make a judgment on everything about the measurement at the site. In general, UAVs observation has so many advantages in the point of view of high spatial resolution and frequency of measurement, but UAVs observation is weak against gust and uneven sunshine condition. For example, it is difficult to acquire high quality data under gust condition which vibrate the main body of UAVs. Moreover, such a condition increases the risk of accident like a crash into the ground. On the other hand, uneven sunshine condition impedes the acquisition of images with uniform brightness because one flight needing several minutes for measurement of the specific area. General caution points before a flight are described in the below in order to safe flight of UAVs.

Box 2.10.6.1 Important points for consideration when preparing a field campaign with a UAV

Validation of the intensity level of GPS/IMU/Magnetic sensor
Check of lifetime of battery against temperature
Validation of rotors and wing
Validation of intensity level of radio control signal
Software
Check of the flight course
Check of flight height
Check of overlap and side lap ratio
Check of orientation angle of the UAV head
Environmental condition
Confirmation of legal flight area
Check of the place for take-off and landing
Check of wind/temperature/rainfall/ visibility conditions
Check of the existence of an obstacle
Check of the existence of birds
Check of the existence of human activity
Emergency response plans
GPS signal lost condition
Radio control signal lost
Low battery condition
Response to the crash accident

2.10.7.3 Case Study: Preliminary Amazonian rainforest measurement using UAV-borne Camera system and UAV-borne LIDAR system at INPA's ZF-2 site, Amazonas, Brazil

Amazon forest is located at the tropical basin of the Amazon River, and area is very large and moreover forest type is rainforest. Even an access into the forest from the road or a river is quite difficult for a frontier. In order to improve deeply the understanding of Amazonian forest phenomena, UAVs are one of the required remote sensing instruments.

On September 21st-22th 2013, the developed UAV-borne Camera system and UAV-borne LIDAR system were demonstrated at INPA'S ZF-2 experimental forest site, Amazonas, Brazil. Figure 1.3.1. shows an overview of observation using UAV-borne camera system at the site. The characteristics of the site existed several limitations for UAV flight. Specifically, the space for take-off and landing was restricted by the roadside tall trees. And, intensity of GPS signal on the road sometimes unexpectedly become low at specific time. Moreover, in case of a sunny day, wind velocity became strong after 9 or 10 a.m. due to a strong upward air current from the forest.

Figure 1.3.1. Overview of observation using UAV-borne camera system at ZF-2.

Figure 1.3.2. The developed laser unit and a monitor camera.

Main hardware were UAV, Camera and laser unit and the MD-4 1000 (microdrones GmbH, Germany) as a multi rotor UAV, Olympus EP-1 (Olympus, Japan) as an acquisition of imagery and LD-MRS400001 (SICK, Germany) as a laser scanner were used, respectively. Specification of laser scanner was almost same as the Ibeo Lu Automotive Laser scanner Jaakkala et al. (2011) used. Our LIDAR unit has a monitor camera (Figure 1.3.2). Our UAVs were customized to high humidity to avoid rusty of cables. Since the ZF-2 area was high humidity through the year, all cable connection ports were covered by the packing.

The synchronization of the different instruments is carried out electronically. In case of UAV-borne Camera system, firstly, geographical position and posture information on UAV at each acquisition time of image was generated by using a time stamp in the image header, and secondly, mosaic data was generated by using the pix4UAV software which was able to carry out SfM technique. On the other hand, in case of UAV-borne LIDAR system, firstly, the geographical position and the posture information on UAV at each acquisition time of the laser beam was generated, and secondly, the geographical position of target was calculated, and finally, DSM and DEM data at nadir angle (from -10 degrees to +10 degrees) were generated by the original software, respectively. Figure 1.3.3. shows the mosaic data which was generated from 1,200 images derived from UAV-borne camera system at 300 m x 600 m plot (namely Quadradão) in ZF-2. Higher brightness area of the canopy was affected by the uneven sunshine condition. DSM was generated from images, and DEM was SRTM. Figure 1.3.4. shows DSM and DEM generated from UAV-borne LIDAR system. Henceforth, the accuracy of these results are going to be validated using the ground inventory data.

Figure 1.3.3. Mosaic data generated from UAV-borne camera system. DSM was from images, and DEM was STRM.

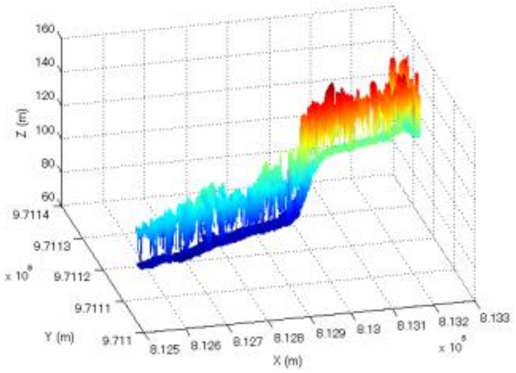


Figure 1.3.4. DSM and DEM generated from UAV- borne LIDAR system.

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2.10.8 Modelling and forecasting forest-cover change

Most models of forest-cover change at the landscape to the national scales address one of the following questions (sometimes they deal with the two at once): (i) which locations are most likely to be affected by forest-cover change in the near future? (ii) At what rate are forest-cover changes likely to proceed in a given region?

Predicting the location of future forest-cover change is a rather easy task, provided that current and future processes of forest-cover change are similar to those that operated in the recent past. Statistical relationships are calibrated between landscape determinants of land-use changes (e.g., distance to roads, soil type, market accessibility, terrain) and recently observed spatial patterns of forest-cover change. The analysis of spatially-explicit deforestation maps, i.e. generated to estimate activity data for IPCC reporting, can provide a suitable database for such analysis. Both the shape and pattern of the deforestation observed (location, size, fragmentation), as well as, their relationship with spatial factors influencing forest change can be quantified and empirical relationship established. Such understanding can drive spatially-explicit statistical models are then used to produce a *suitability map* for a given type of forest-cover change. Such models are born from the combination of geographic information systems (GIS) and multivariate statistical models. Their goal is the projection and display, in a cartographic form, of future land use patterns which would result from the continuation of current land uses. Note that regression models cannot be used for wide ranging extrapolations in space and time.

Predicting future rates of forest-cover changes is a much more difficult task. Actually, the quantity of deforestation, forest degradation, or forestation in a given location depends on underlying driving causes. These indirect and often remote causes of forest-cover change are generally related to national policies, global markets, human migrations from other regions, changes in property-right regimes, international trade, governance, etc. The relative importance of these causes varies widely in space and time. Opportunities and constraints for new land uses, to which local land managers may respond by changing forest cover, are created by markets and policies that are increasingly influenced by global factors (Lambin et al., 2001). Extreme biophysical events occasionally trigger further changes. The dependency of causes of land-use changes on historical, geographic and other factors makes it a particularly complex issue to model. Transition probability models, such as Markov chains, project the amount of land covered by various land use types based on a sample of transitions occurring during a previous time interval. Such simple models rely on the assumption of the stationarity of the transition matrix - i.e. temporal homogeneity. The stochastic nature of Markov chain masks the causative variables.

Many economic models of land-use change apply optimization techniques based either on whole-farm analyses at the microeconomic level (using linear programming) or general equilibrium models at the macroeconomic scale (Kaimowitz and Angelsen, 1998). Any parcel of land, given its attributes and its location, is modeled as being used in the way that yields the highest rent. Such models allow investigation of the influence of various policy measures on land allocation choices. The applicability of micro-economic models for projections is however limited due to unpredictable fluctuations of prices and demand factors, and to the role of non-economic factors driving forest-cover changes (e.g., corruption practices and low timber prices that underlie illegal logging).

Dynamic simulation models condense and aggregate complex ecosystems into a small number of differential equations or rules in a stylized manner. Simulation models are therefore based on an a priori understanding of the forces driving forest-cover change. The strength of a simulation model depends on whether the major features affecting land-use changes are integrated, whether the functional relationships between factors affecting change processes are appropriately represented, and on the capacity of the model to predict the most important ecological and economic impacts of land-use changes. Simulation models allow rapid exploration of probable effects of the continuation of current land use practices or of changes in cultural or ecological parameters. These models allow testing scenarios on future land-use changes. When dynamic ecosystem simulation models are spatially-explicit (i.e., include the spatial heterogeneity of landscapes), they can predict temporal changes in spatial patterns of forest use.

Agent-based models simulate decisions by and competition between multiple actors and land managers. In these behavioral models of land use, decisions by agents are made spatially-explicit thanks to cellular automata techniques. A few spatially-explicit agent-based models of forest-cover change have been developed to date. These grid-cell models combine ecological information with socio-economic factors related to land-use decisions by farmers. Dynamic landscape simulation models are not predictive systems but rather game-playing tools designed to understand the possible impacts of changes in land use. Dynamic landscape simulation models are specific to narrow geographic situations and cannot be easily generalized over large regions.

All model designs involve a great deal of simplification. While, by definition, any model falls short of incorporating all aspects of reality, it provides valuable information on the system's behavior under a range of conditions (Veldkamp and Lambin, 2001). Current models of forest-cover change are rarely based on processes at multiple spatial and temporal scales. Moreover, many land use patterns have developed in the context of long term instability (e.g., fluctuations in climate, prices, state policies). Forest-cover change models should therefore be built on the assumption of temporal heterogeneity rather than on the common assumption of progressive, linear trends. Rapidly and unpredictably changing variables (e.g., technological innovations, conflicts, new policies) are as important in shaping land use dynamics as the slowly and cumulatively changing variables (e.g., population growth, increase in road network).

2.10.9 Cloud-computing and web-based approaches to support national forest monitoring

One of the technical challenges which countries may have is to explore the use of remote sensing, and to acquire, manage and process gigabytes or even terabytes of remote sensing data. Technologies are emerging which begin to offer potential solutions to tackle some of these challenges. The advent of large-scale, secure, hosted (also known as "cloud-based") databases and data processing platforms can offer shared access to large catalogs of data and computational resources for processing. The current trends in technology adoption, internet access and "Digital inclusion" policies in the developing world suggest that cloud-based remote sensing processing can offer a complementary solution for the increasingly useful role of remote sensing and the increasing issues of transparency.

As an example, one such platform in evolution is *Google Earth Engine*, which has been developed as a new technology platform that enables automated remote sensing and ground-sampled data processing and forest mapping (Figure 2.10.4). The platform allows remote sensing scientists and developing world nations to directly build and advance the algorithms in order to advance the broader operational deployment of existing scientific methods, and strengthen the ability for public institutions and civil society to map better and understand the state of their forests and changes. The initial release of Earth Engine includes essentially the complete Landsat archive of L5 and L7 data[105], collected over more than twenty-five years (1984-present), for many of the tropical countries. The platform includes open access to computational resources and tools for creating spatial and temporal mosaics over these datasets, with or without atmospheric correction as desired and to run automated mapping and monitoring algorithms using these data. The platform includes a new application programming interface (API) that allows scientists access to these computational and data resources, to scale their current algorithms or develop new ones. A final important element is the portal for integration of ground-sampled data into this platform; including data from smartphones used in trials in community-based forest monitoring (see section 3.4.2 on how communities can make their own forest inventories).

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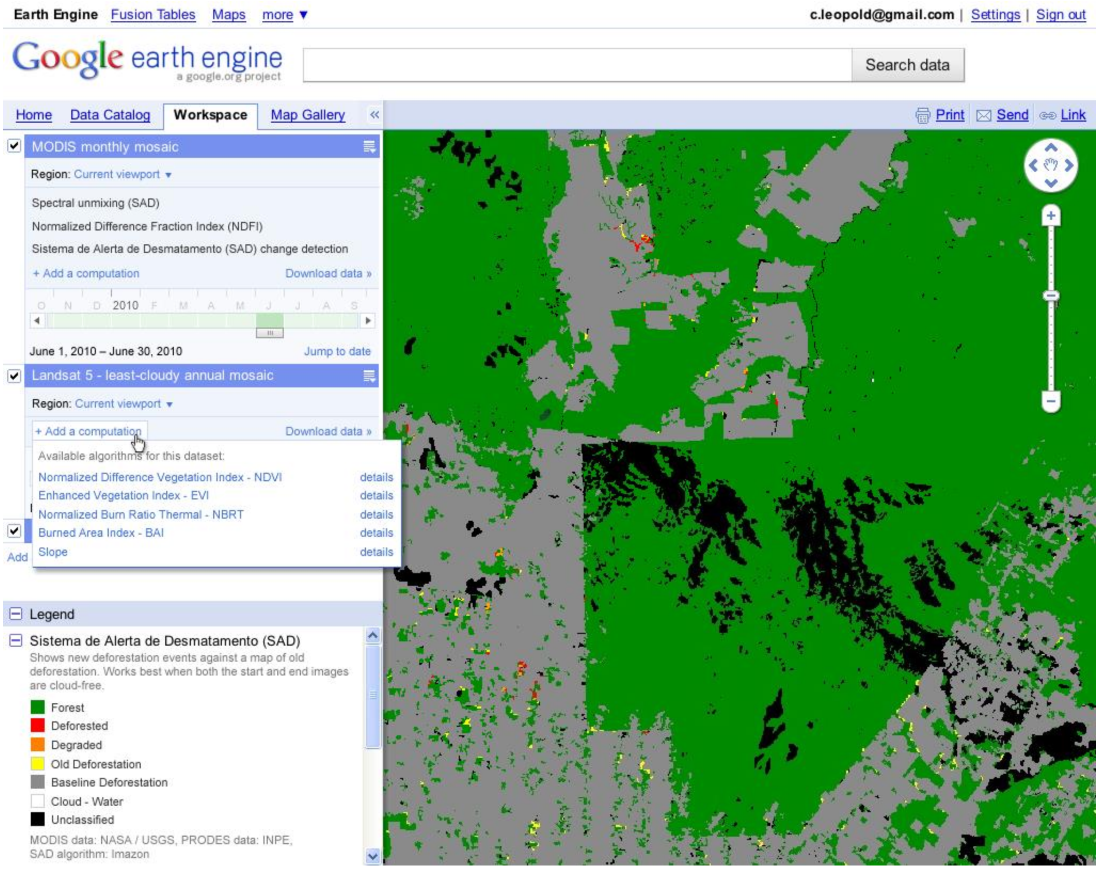
[105] This includes all Landsat L5/L7 data held at the USGS EROS Data Center as of November, 2010, at <= 50% cloud-cover, a threshold recommended by USGS.

Figure 2.10.4. Results of running Imazon's forest change analysis in Google Earth Engine on satellite imagery taken between March and June, 2010. The green colour represents forested areas, while the red and yellow areas indicate recent deforestation. The analysis indicates that no deforestation took place inside the Surui territory during this period, whereas along the perimeter and outside of their territory there is evidence of recent deforestation.



Such technologies have advantages for countries with limited existing remote sensing capacities and that are not able to process large amounts of remote sensing data and are interested to make use of some of the archived data. These new technologies also present their own challenges such as feasibility in areas of little-to-no Internet access and concerns about data privacy, ownership and security of the data. The automated mapping algorithms require locally-relevant training data and forest definitions in order to produce maps which respect different definitions of forests, deforestation and degradation. The use and value for national level reporting still need to be explored fully.

2.10.10 Summary and recommendations

The techniques and approaches outlined in previous sections are considered to have significant potential to improve national monitoring and assessing carbon emissions from deforestation and forest degradation for REDD+ implementation. Their usefulness should be judged by a number factors including:

- Data characteristics & spatial/temporal resolution of current observations/sensors
- Operational calibration and interpretation/analysis methods

- ☐ Area of contribution to existing IPCC land sector reporting and sourcebook approach
- ☐ Estimated monitoring cost (i.e. per km^2)
- ☐ Experiences for monitoring purposes, i.e. examples for large scale or national demonstration projects
- ☐ Data availability, coverage and access procedures
- ☐ Known limitations and challenges, and approaches to deal with them
- ☐ National capacities required for operational implementation
- ☐ Status, expected near-term developments and long-term sustainability

There is a clear role for the international community to assist countries and actors involved in REDD+ monitoring in the understanding, usefulness and progress of evolving technologies. This involves a proper communication on the activities needed and actions taken to evaluate and prototype REDD+ monitoring using data and techniques becoming increasingly available. Near-term progress is particularly expected in the availability and access to suitable remote sensing datasets. Currently Landsat data are the most common satellite dataset for forest monitoring on the national level. Several factors are responsible for this including rigorous geometric and radiometric standards, the image characteristics most known and useful for large area land cover mapping and dynamics studies, and the user-friendly data access policy. Thus, there are important differences in the usefulness of existing data sources depending on the following characteristics:

I. Observations are being continuously acquired and datasets archived by national or international agencies;

II. There is general understanding on the availability (i.e., global cloud-free coverage), quality and accessibility of the archived data;

III. Data are being pre-processed (i.e. geometrically and radiometrically corrected) and are made accessible to the monitoring community;

IV. Pre-processed datasets are available in international or national mapping agencies for land cover and change interpretation;

V. Sustained capacities exist to produce and use land cover datasets within countries and for global assessments (e.g., in developing countries).

Existing and archived satellite data sources are not yet fully explored for forest monitoring. Ideally, all relevant observations (satellite and *in situ*) should meet a set of six requirements in Table 2.10.3 to be considered fully useful and operational. Table 2.9.4 further emphasizes that active satellite remote sensing data (i.e. radar and Lidar) are becoming more available on a continuous basis and suitable for change analysis. This will enable better synergistic use with current optical sensors, to increase frequency of cloud free data coverage and enhance the detailed and accuracy of monitoring products.

The international Earth observation community is aware of the needs for pre-processed satellite data being available in developing countries. The gap between acquiring satellite observations and their availability (in the archives) and processing the data in a suitable format to be ready for use by developing countries for their forest area change assessments is being bridged the space agencies and data providers such as USGS, NASA, ESA, JAXA, INPE, and international coordination mechanism of CEOS, GOFC-GOLD and GEO. These efforts will in the next few years further decrease the amount of costs and efforts to use satellite observations for national-level REDD+ monitoring.

Table 2.10.3. Current availability of fine-scale satellite data sources and capacities for global land cover change observations given six general requirements (Note: dark gray=common or fully applicable, light gray=partially applicable/several examples, white=rare or no applications or examples).

	Satellite observation system/program	Technical observation challenges solved	Access to information on quality of archived data worldwide	Continuous observation program for global coverage	Pre-processed global image datasets generated & accessible	Image data available in mapping agencies for land change analysis	Capacities to sustainably produce/ use map products in developing countries
OPTICAL	LANDSAT TM/ETM	■	■	■	■	■	▒
	ASTER	■	■	▒	▒ On demand	▒	
	SPOT HRV (1-5)	■	■	■	▒ Commercially	▒	▒
	CBERS 1-3	■	▒	▒	▒ Regionally		
	IRS / Indian program	■	▒	▒	▒ Regionally		
	DMC program	■	▒	▒ Probably	▒ Commercially		
SAR	ALOS/PALSAR + JERS	■	■	■	▒ Regionally		
	ENVISAT ASAR, ERS 1+2	■	■	■	▒ Regionally		
	TERRARSAR-X	■	▒		Commercially		
	IKONOS, GEOEye	■	■	▒ Probably	Commercially		
	ICESAT/GLAS (LIDAR)	▒	■				

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3 LULUCF GHG REPORTING SYSTEM IMPLEMENTATION

3.1 PRACTICAL EXAMPLES

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3.1.1 Scope of Section

Given the heterogeneity that characterizes the landscape of most Annex-1 Parties, the estimation of GHG emissions and removals from the Land Use, Land-Use Change and Forestry (LULUCF) sector represents one of the most challenging aspects of national GHG inventories. This is also witnessed by the fact that, based on the information submitted annually to the UNFCCC[106], it emerges that the LULUCF sector of many Annex-1 Parties is still not fully complete (in terms of categories and carbon pools), and that uncertainties are still rather high. However, given the reporting requirements under the Kyoto Protocol (from 2010), significant improvements are apparent and ongoing.

This heterogeneity is also reflected in the methods used by Annex-1 Parties to estimate GHG emissions and removals from the LULUCF sector, which largely depend on national circumstances, including available data and their characteristics.

For the category "forest land", for most Annex-1 Parties, forest inventories provide the basic inputs for both activity data (area of forest and conversions to/from forest) and the carbon stock change factors in the various pools. Furthermore, the use of satellite data is not yet very common for LULUCF inventories, although the situation is rapidly changing with the now freely availabile Landsat images. Exceptions already exist, with some countries without forest inventories relying heavily on satelite data and modelling approaches.

This section provides a short overview of the variety of methods used by Annex-1 Parties for estimating forest area changes (3.1.2), carbon stock changes (3.1.3) and the related uncertainties (3.1.4). It also includes two relevant examples illustrating how empirical yield-data driven modelling (Canada) and process modelling (Australia) can be used to estimate GHG emissions and removals from LULUCF.

3.1.2 Methods for estimating forest area changes

The identification of the activity data (area of a land use category, e.g. forest land) often represents the most difficult step for a LULUCF GHG inventory, particularly for the areas subject to land use changes (e.g. to/from forest). For example, until 2009, about 30% of Annex-1 Parties did not report *land converted to forest* (often included in the category

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[106] National inventory reports by Annex-1 Parties can be found at: http://unfccc.int/national_reports/annex_i_ghg_inventories/items/2715.php

forest remaining forest) and about 50% did not yet report deforestation. This situation improved significantly since 2010, when the accounting of Afforestation/Reforestation and Deforestation since 1990 became mandatory with the first year of the reporting under the Kyoto Protocol.

Depending on the available data, various methodologies are applied by Annex I countries to generate the time series for annual activity data. Most of the methodologies do not generate data with annual time steps. As such, interpolation or extrapolation are widely used to produce the annual data needed.

Given its probable importance in the future REDD+ implementation, here we mainly focus on the role of remote sensing.

According to the information available from the National Inventory Reports (NIR) (Table 3.1.1), only 23 Annex-1 Parties (about 60%) indicated the use of some remote sensing techniques (or the use of related products, e.g., Corine Land Cover) in the preparation of their GHG inventories. Generally, these countries integrated the existing ground-based information (e.g., national statistics for the agricultural, forestry, wetland and urban sectors, vegetation and topographic maps, climate data) with remote sensing data (e.g., aerial photographs, satellite imagery using visible and/or near-infrared bands, etc.), using GIS techniques.

The following remote sensing techniques were used:

1) Aerial photography: although analysis of aerial photographs is considered one of the most expensive methods for representing land areas, 11 Annex-1 Parties used it in combination with ground data, and in some cases, with other techniques or land cover maps (e.g. CORINE Land cover), to detect land use and land use changes. For instance, France used 15,600 aerial photographs together with ground surveys (TerUti LUCAS). Although these images are sometimes characterized by different spatial resolution and quality, they permit accurate monitoring of land use and land use changes in the past.

2) Satellite imagery: (using visible and/or near-infrared bands and related products): few countries used detailed satellite imagery in the visible and/or near-infrared bands for representing land areas.

For example, Australia combined coarse (NOAA/AVHRR) and detailed (LANDSAT MMS, TM, ETM+) satellite imagery to obtain long time series of data (see section 3.1.4.1 for further details). Canada uses satellite imagery to support the development of forest inventories for the compilation of activity data on natural disturbances, and to detect and monitor deforestation events. Canada uses LANDSAT, SPOT, IRS (Indian Remote Sensing System), QuickBird and WorldView imagery, and Google maps (based on LANDSAT and QUICKBIRD).

New Zealand based their Land Cover Database (LCDB1 and 2) on SPOT (2 and 3) and LANDSAT 7 ETM+ satellite imagery; mapping of land use in 2009 will use SPOT 5 satellite imagery. Within the LUCAS project (Land Use and Carbon Analysis System), the location and timing of forest harvesting will be identified with medium spatial resolution (250 m) MODIS satellite imagery, while the actual area of harvesting and deforestation will be determined with high resolution satellite systems or aerial photography.

France used numerous satellite images for representing land areas of French Guyana: in total, 16,786 ground points were analyzed in 1990 and 2006 using LANDSAT and SPOT imagery, respectively.

Table 3.1.1. Use of Remote Sensing in Annex I Countries, as reported in their National Inventory Reports in 2008 (from Achard et al. 2008).

Annex-I Countries	Aerial Photography	Satellite imagery (using visible and/or near-infrared bands and related products)				Satellite or airborne radar imagery	Airborne LIDAR
		Coarse resolution	Medium resolution	Fine resolution	CORINE (CLC)		
Australia	Yes	Yes	Yes				
Austria							
Belgium					Yes[4]		
Bulgaria							
Canada	Yes		Yes	Yes[2]			
Croatia							
Czech Republic					Yes		
Denmark							
Estonia					Yes[4]		
Finland			Yes[5,6]				
France	Yes		Yes[5]				
Germany					Yes[4]		
Greece							
Hungary					Yes[4]		
Iceland			Yes		Yes[1]		
Ireland					Yes		
Italy	Yes		Yes[1]		Yes[4]		
Japan	Yes[4]						
Latvia							
Liechtenstein	Yes						
Lithuania							
Luxembourg	Yes		Yes[1]				
Monaco							
Netherlands			Yes[1]				
New Zealand	Yes	Yes[1]	Yes	Yes[1]		Yes[1]	Yes[1]
Norway	Yes						Yes[3]
Poland							
Portugal					Yes[4]		
Romania							
Slovakia							
Slovenia							
Spain					Yes[4]		
Sweden			Yes[4,5,6]				
Switzerland	Yes						
Turkey					Yes[4]		
Ukraine							
United Kingdom							
USA	Yes		Yes[6]				

Notes: 1. Use of this methodology planned in the future; 2. Methodology reported in previous NIR but not in the latest; 3. The intention to use this methodology reported in previous NIR but not in the latest; 4. Methodology used only for reporting of some IPCC categories; 5. Methodology used only for reporting of a portion of territory of the Country; 6. Methodology not specified. Note that NIRs by Russian Federation and Belarus were not included in this analysis because only available in Russian.

Some European countries reported use of satellite imagery for supporting stratification of their national forest inventory. Furthermore, 10 countries used existing land cover maps, like the CORINE products (1990 and/or 2000 maps, and the associated change product), that are based on interpretation of satellite imagery and their verification through ground surveys. For example, Czech Republic and Ireland used the CORINE products for reporting all the categories indicated by the IPCC (Penman et al. 2003), whereas other countries used the CORINE Land Cover map (CLC) to report only some IPCC categories, like Estonia (organic soils), Hungary (wetlands), Germany, Italy, Portugal, Spain and Turkey.

3) Satellite or airborne radar imagery: no countries reported the use of satellite or airborne radar imagery for representing land areas. New Zealand may use satellite radar within the LUCAS project to identify the location and timing of forest harvesting if the evaluation of using medium spatial resolution (250 m) MODIS satellite images is unsuccessful.

4) Airborne LIDAR: only New Zealand reports the use of airborne LiDAR in combination with field measurements to estimate the changes in carbon stocks for 2008 in forests planted after January 1st 1990, within plots established on a 4 km grid across the country. The LIDAR data are calibrated against the field measurements, and LIDAR data will be processed to provide the total amount of carbon per plot only for forest plots that are inaccessible; the measurement process on the same plots will be repeated at the end of the Kyoto Protocol's commitment period (around 2012). In 2011, Canada had flown 34 LIDAR transects over 25,000 km, and results are being analyzed for potential future use in NIR reporting (e.g. Magnussen and Wulder 2012).

In conclusion, some countries – typically characterized by large land areas not easily accessible - make direct use of satellite-remote sensing for GHG inventory preparation. By contrast, most European countries - typically characterized by more intensive land management, and by a long tradition of forest inventories – at the moment, do not use satellite-remote sensing, or only use derived products such as CORINE, at least for gathering ancillary information. In these cases, forest area and forest area changes are determined through other methods, including permanent plots, forest and agricultural surveys, census, registries, or observational maps.

Thus, in most cases, the use of satellite data for LULUCF inventories by Annex-1 Parties is currently not as important as it will likely be for REDD+. However, the situation seems in rapid development, as several Annex I countries have indicated the intention to use more remote sensing data in the near future (e.g., Italy, Netherlands, Denmark, Luxembourg, Iceland).

3.1.3 Methods for estimating carbon stock changes

As explained in Section 2.3, the approaches used to assess the changes of carbon stocks in different carbon pools are essentially two: the gain-loss method (sometimes called the IPCC default), which estimates the net balance of additions to, and removals from a carbon pool, and the stock change (or stock-difference) method, which estimates the difference in carbon stocks in a given carbon pool at two points in time. While the gain-loss can be applied with all tier levels, the stock change approach typically requires a detailed national forest inventory.

In general, for the category "forest land", the most important pool in terms of carbon stock changes is the aboveground biomass, both for the removals (e.g., in "land converted to forest", and "forest remaining forest") and for the emissions (e.g., deforestation); however, some exceptions may also occur, e.g., emissions from organic soils may be more important over time than carbon stock changes in biomass.

For the aboveground biomass pool of forests, the majority of Annex-1 Parties either use the gain-loss, or a mix of the two approaches, depending on the quality of the available data; in this case, tier 2 or tier 3 methods are typically applied, i.e., the inputs for calculating carbon stock changes are country-specific data on growth, harvest and natural disturbances (e.g., forest fires, storms), often based on or complemented by yield models (e.g., UK, Italy, Ireland). Countries which use the stock change method include Sweden, Germany, Spain, Belgium, Bulgaria, Greece, Estonia Slovenia, and the U.S.; in these cases, the difference in stocks are calcualted with annual time steps or over longer periods (e.g., Germany). Countries that use the gain-loss method include Australia and Canada. Both approaches typically use (directly or indirectly) timber volume or growth data collected through regional / national forest inventories, or through forest management plans (common in Eastern European countries). The conversion from timber volume into carbon stock is generally done with country-specific biomass functions (e.g., Austria, Canada, Finland, Ireland and Spain), or biomass expansion factors. For belowground biomass, most countries use default or country-specific ratios of aboveground to belowground biomass.

When using the stock-change method for a specific land-use category, it is important to ensure that the area of land in that category at times t1 and t2 is identical, to avoid confounding stock change estimates with area changes. Ignoring this simple rule is a relatively common mistake which may significantly affect estimates of emissions and removals.

Using the gain-loss method requires high quality activity data including areas annually affected by forest management, natural disturbances and land-use change. Use of such detailed data also allows for the attribution of observed emissions and removals to the primary drivers. This is not readily possible with the stock-change method because the causes of the observed changes in stocks are often unknown or not reported. Moreover, model-based systems that use the gain-loss method can seamlessly transition from monitoring (using actual activity data) to projection (using scenario assumptions about future activity data). This is especially useful for policy analyses, REDD+ scenario development, and the calculation of reference levels and forward-looking baselines.

When possible, comparing the two methods (gain-loss and stock-change), and providing explanations for any major observed differences, is useful for verfication, which helps to identify potential errors and may help build confidence in the estimates.

For the reporting of the other pools (dead wood, litter and soils) the situation is variable. In several cases, due to the lack of appropriate data, the tier-1 method is used, which assumes no change in carbon stock (except for drained organic soils) in cases of no change in land uses (e.g., forest remaining forest, or forest management). For dead wood and mineral soils, this assumption is applied by about 20% and 40% of Annex-1 countries, respectively (Table 3.1.2); the other countries use either country-specific factors or models (i.e., tier 2 and 3 methods). In cases of land-use change (from or to forest), the carbon stock changes of these pools is generally assessed by the difference of carbon stock reference values (in most cases country-specific and appropriately disaggregated) between the two land uses. In specific cases (e.g., dead wood in Afforestation/Reforestation), it is often assumed that no change in C occurs.

It should be noted that, under the Kyoto Protocol (Decision 15/CMP.1, para 6(e)), all C pools should be accounted, unless evidence is provided that these pools are not sources. Such evidence could be based on one or more elements (including reasoning of likely system responses, scientific literature, etc.) which, although not enough to quantify an accurate sink estimate, strongly suggest that the pool is not a source.

Table 3.1.2. Completeness of reporting of C pools under the Kyoto Protocol among Annex I countries (% of countries reporting an estimate):

	Above-ground biomass	Below-ground biomass	Litter	Dead wood	Soil Min	Soil Org
Afforestation/Reforestation	97%	97%	81%	53%	89%	46%
Deforestation	97%	97%	94%	94%	94%	47%

Forest Managment[1]	100%	100%	70%	78%	57%	65%

[1] % calculated for those countries which elected FM

3.1.4 National carbon budget models

This section illustrates two relevant examples of tier-3 models for estimating GHG emissions and removals from forests: an empirical yield-data driven model (Canada, 3.1.4.1) and a satellite data-driven process model (Australia, 3.1.4.2).

3.1.4.1 The Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)

For over two decades, Natural Resources Canada's Canadian Forest Service (CFS) has been involved in research aimed at understanding and modelling carbon dynamics in Canada's forest ecosystems. In 2001, the CFS in partnership with Canada's Model Forest Network, set out to design, develop, and distribute an operational-scale forest carbon accounting modelling software program to Canada's forestry community. The software would give forest managers, be they small woodlot owners or provincial or industrial forest managers, a tool with which to assess their forest ecosystem carbon stocks, and forest management planning options in terms of their ability to sequester and store carbon from the atmosphere.

The CBM-CFS3 (Kurz et al. 2009) was also developed to be the central model of Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) (Kurz and Apps 2006), which is used for international reporting of the carbon balance of Canada's managed forest (Stinson et al. 2011). Its purpose is to estimate forest carbon stocks, changes in carbon stocks, and emissions of non-CO_2 greenhouse gases in Canada's managed forests. The NFCMARS is based on an empirical yield-data driven model approach. It is designed to estimate past changes in forest carbon stocks—i.e., from 1990 to the current reporting year (monitoring)—and to predict, based on scenarios of future disturbance rates, land-use change and management actions, changes in carbon stocks from the current reporting year into the future (projection).

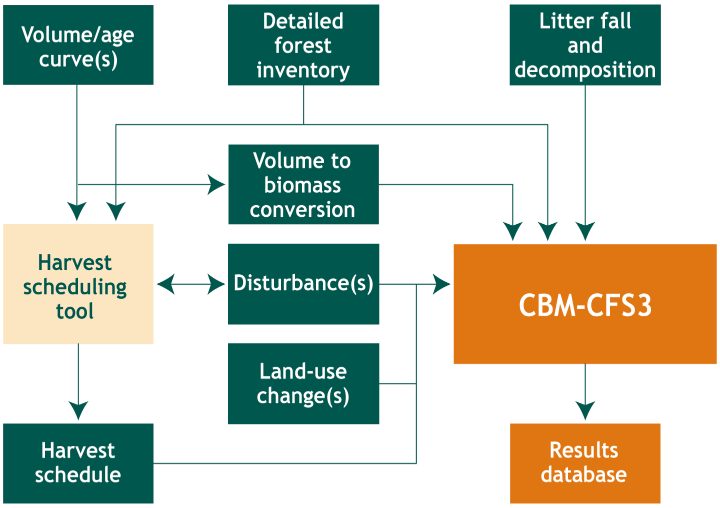
The system integrates information - such as forest inventories, information on forest growth and yield obtained from temporary and permanent sample plots, statistics on natural disturbances such as fires and insects, and land-use change and forest management activities. Following IPCC guidance, dynamics of dead wood, litter, and soil C pools are simulated using a process modelling approach that represents inputs to these pools from biomass pools to account for turnover (litterfall, fine root turnover, etc.), stand mortality (e.g., declining yield curves in overmature stands) and disturbances (fires, insects, harvesting). Losses from these pools result from decomposition and disturbances (e.g., fire and salvage logging). The NFCMARS modelling framework incorporates the best available information and scientific understanding of the ecological processes involved in forest carbon cycling (Figure 3.1.2). Key elements of the System include:

- **The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)**
- **Tracking Land-Use Change** (monitoring area affected and resulting changes in carbon stocks that result from afforestation, reforestation, or deforestation activities in Canada)
- **Forest Inventory** (area-based inventory approach for the managed forest)
- **Forest Management and Disturbance Monitoring** (use the best available statistics on forest management and natural disturbances, obtained from the

National Forestry Database program, the Canadian Wildland Fire Information System, and from provincial and territorial resource management agencies)

- **Spatial Framework** (A nested ecological framework, consisting of 18 reporting zones based on the Terrestrial Ecozones of Canada. Beneath these, 2 layers of nested spatial units comprised of 60 reconciliation units and over 500 management units are included. Stinson et al. 2011)
- **Special Projects** to advance the scientific basis of the NFCMARS, a number of special research, monitoring and modelling projects are conducted (Fluxnet studies, adding spatially explicit modelling, dead organic matter calibration, and uncertainty and sensitivity analysis, e.g., White et al. 2008, Smyth et al. 2010; Hilger et al. 2012, Shaw et al. 2013).

Figure 3.1.2. CBM-CFS3 uses data from forest management planning and activity data from disturbance and land-use change monitoring for national-scale integration of forest C cycle information.



Main outputs:

- **National Inventory Report** (as with every Annex-1 country, Canada prepares an annual National Inventory Report detailing the country’s greenhouse gas emissions and removals, as per United Nations Framework Convention on Climate Change guidelines (UNFCCC) http://www.ec.gc.ca/ges-ghg/).
- **Other UNFCCC requirements.** The system is also used to calculate forward-looking reference levels and other information required for UNFCCC reporting and decision making (e.g. Kurz et al. 2008).
- **Policy Development Support** (work with policy makers in both the federal and provincial governments to ensure forest policy development is supported by sound science)

The CBM-CFS3 is a stand- and landscape level modelling framework that simulates the dynamics of all forest carbon stocks as well as the CO_2 and non-CO_2 GHG emissions and removals required under the UNFCCC. It is compliant with the carbon estimation methods of the Tier-3 approach outlined in the GPG2003 and in the 2006 IPCC Guidelines for the AFOLU sector.

The model builds on information used for forest management planning activities (e.g., forest inventory data, yield tables, natural and human-induced disturbance information, forest harvest schedules and land-use change information), supplemented with information from national ecological parameter sets, climate and volume-to-biomass equations appropriate for Canadian species and forest regions.

The CBM-CFS3 can be used in spatially-referenced and spatially-explicit modes depending on the available input data, and limited by the scale of the analysis: spatially-explicit approaches are currently limited to project-level or regional applications.

Although the model currently contains a set of default ecological parameters appropriate for Canada, all model parameters can be modified by the user, allowing for the application of the model in other countries. The user interface can be displayed in English, French, Spanish, or Russian. The CBM-CFS3, supporting software, and user documentation, are available free-of-charge at https://carbon.nfis.org/cbm.

International activities

The CFS Carbon Accounting Team (CAT) holds CBM-CFS3 training workshops across Canada, and occasionally, in countries where official government collaborations exist. Many foreign experts have also been trained in the use of the model. Interest in Canada's innovative approach to forest GHG modelling and reporting through the NFCMARS has been growing. In 2005, NRCAN began a bilateral project with the Russian Federal Forest Agency to share knowledge and approaches to forest carbon accounting with scientists in Russia where the model has been used for regional- and national-scale analyses. More recently, the CFS-CAT began a collaborative project with CONAFOR (Comisión Nacional Forestal), the Government of Mexico's Ministry of Forests, to assess and test the suitability of the CBM-CFS3 in the wide range of forests and climates of that country. The aim of the project is to determine whether the model could contribute towards Mexico's GHG accounting system and towards Mexico's efforts to account for the effects of reducing emissions from deforestation and degradation (REDD). The model can be used in REDD+ or project-based mitigation efforts to provide both the baseline and the with-project estimates of GHG emissions and removals. Collaboration with Mexico also focuses on the use of increasingly available remote-sensing data on land-cover change as input to analyses of changes in GHG emission and removal estimates using the CBM-CFS3 because the use of simple emission factors is not sufficient to account for the complex dynamics over time following land-use change involving forests.

A collaborative project with the Joint Research Centre of the European Commission is also ongoing. The model has been applied to different silvicultural systems in Europe, with the long-term objective of quantifying national-scale forest C dynamics of European countries.

The CFS-CAT is continuing to develop and refine the CBM-CFS3 to accommodate improvements in the science of the forest carbon cycle, changes in policy surrounding climate change and forests, and changes to broaden the use and applicability of the model in other ecosystems. For more information visit: http://carbon.cfs.nrcan.gc.ca.

3.1.4.2 National Carbon Accounting System (NCAS) of Australia

The NCAS was established by the Australian Government in 1998 to monitor comprehensively, greenhouse gas emissions at all scales (project through to national), with coverage of all pools (living biomass, debris and soil), all gases (CO_2 and non-CO_2), all lands, and all activities. The approach is spatially and temporally explicit, and inclusive of all lands and causes of emissions and removals, including climate variability. It is currently the only example of the full application of a Tier 3, Approach 3 modelling system.

The NCAS represents one of the few examples of a fully integrated, purpose built carbon accounting system that is not based around a long-term national forest inventory (which did not exist in Australia). The system was designed specifically to meet Australia's international reporting needs (UNFCCC and Kyoto) as well as supporting project based accounting under future market mechanisms. The key policy issues that the system was designed to address were:

- Nationally consistent reporting for all lands
- Reporting of emissions and removals for 1990
- Sub hectare reporting as required by the Kyoto protocol
- Geographic identification of projects

A key issue faced by Australia in developing the NCAS was the lack of complete and consistent national forest inventory information, especially in the woodland forests where the majority of Australia's land use change occurs. Implementing a national forest inventory was considered as an option, but was rejected as it would have been extremely costly to establish and maintain, would not have provided the information required to develop an accurate estimate of emissions and removals in 1990 and would not have been able to include all pools and all gases. Instead, Australia developed an innovative system utilizing a variety of ground measured and remotely acquired data sources integrated with ecosystem models to allow for fully spatially explicit modelling. The key elements of the system are:

- The Full Carbon Accounting Model (FullCAM)
- Time series consistent, complete wall-to-wall mapping of forest extent and change in forest extent from 1972 at fine spatial scales (25 m pixel) using Landsat data
- Spatially and temporally explicit climate data (e.g. rainfall, vapour pressure deficit, temperature) and spatially explicit biophysical data (e.g. soil types, carbon contents)
- Species and management information
- Extensive model calibration and validation ground data

The core component of the NCAS is the Full Carbon Accounting Model (FullCAM). FullCAM is best described as a mass balance, C:N ratio, hybrid process-empirical ecosystem model that calculates carbon and nitrogen flows associated with all biomass, litter and soil pools in forest and agricultural systems (Figure 3.1.3). FullCAM uses a variety of spatial and temporal data, tabular and remotely sensed data to allow for the spatially explicit modelling of:

- Forests, including the effects of thinning, multiple rotations and fires
- Agricultural cropping or grazing systems - including the effects of harvest, ploughing, fire, herbicides and grazing
- Transitions between forest and agriculture (afforestation, reforestation and deforestation)

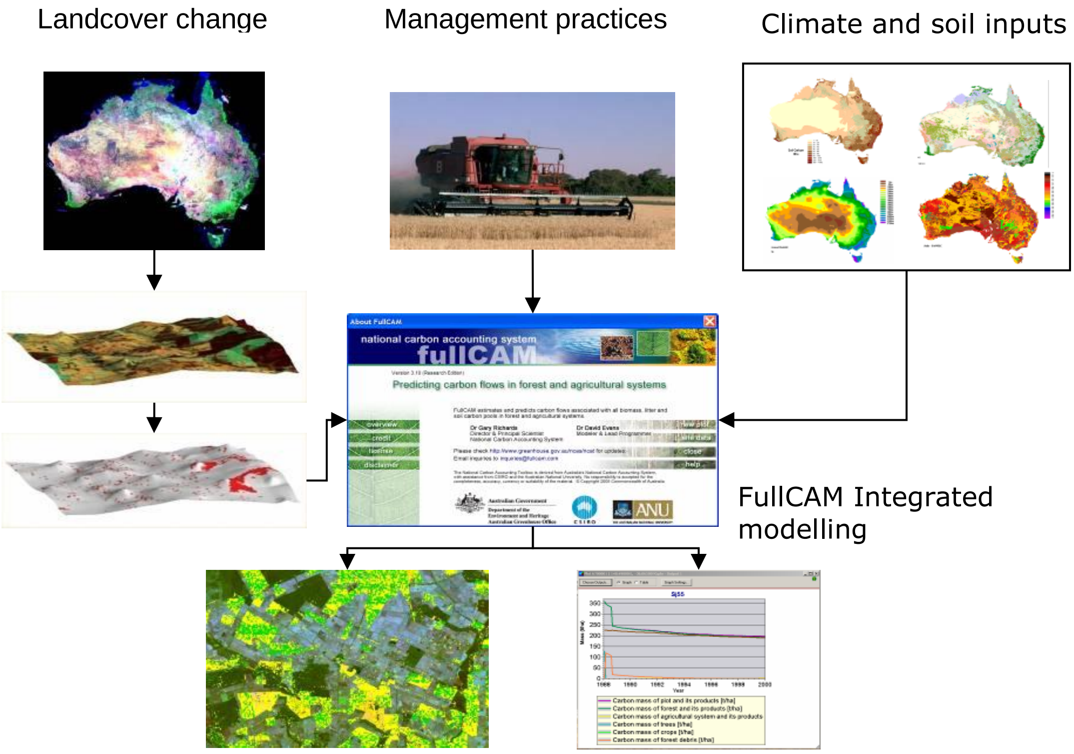
The hybrid approach applied in FullCAM uses process models to describe relative site productivity and the effects of climate on growth and decay, while simple empirical models set the limits and general patterns of growth. Hybrid approaches have the advantage of being firmly grounded by empirical data while still reflecting site conditions. The seamless integration of the component models in a mass-balance framework allows for the use of field-based techniques to directly calibrate and validate estimates. These data have been obtained from a variety of sources including:

- A thorough review of existing data in both the published and unpublished (e.g. PhD theses) literature including biomass, debris and soil carbon
- A comprehensive soil carbon sampling system to validate model results
- Full destructive sampling of forests to obtain accurate biomass measurements

- ❑ Analysis of existing research data for site specific model calibration and testing
- ❑ Ongoing research programs on soil carbon, biomass and non-CO2 emissions

FullCAM, the related data and the NCAS technical report series are freely available as part of the National Carbon Accounting Toolbox (http://www.climatechange.gov.au/ncas/ncat/index.html). The Toolbox allows users to develop project level accounts for their property using the tools and data used to develop the national accounts.

Figure 3.1.3. Graphical depiction of the NCAS modelling framework.



International activities

Australia has developed considerable experience and expertise in developing carbon accounting systems to monitor land use change over the past decade. Australia is currently involved directly with countries such as Indonesia and Papua New Guinea, and indirectly through the Clinton Climate Initiative, to pass on the experiences of developing the NCAS. Rather than promoting the direct application of the Australian NCAS modelling system, the Australian Government is providing policy and technical advice to allow countries to design and develop their own systems to meet their own specific conditions. Like the systems developed by Annex 1 counties, those being developed by less developed countries will differ in their methods and data. However the results of all the systems should be comparable.

3.1.5 Estimation of uncertainties

The majority of Annex-1 Parties performed some uncertainty assessment for the LULUCF sector, but in most cases at tier 1 (error propagation), they did not cover the whole sector, and assessments were often largely based on expert judgment (which can also introduce uncertainty). Estimated uncertainties are generally higher for emissions factors (i.e., carbon stock changes per unit of area) than for activity data (i.e., area of different land uses), e.g., for "forest remaining forest", most of the reported uncertainties for the CO_2 removals by the living biomass were between 25% and 50%, while for the forest area, were generally lower than 20%. Overall, uncertainties of GHG emissions and removals from "forest remaining forest" are usually in the range of 20-40%. For conversions to/from forest, the reported uncertainty is between 25%-30% when such conversions represent relatively small and scattered events (i.e., not easily captured with forest inventories or in general activity data), but may be 10-15% where input data is more certain (e.g., forest plantations, high-resolution mapping of deforestation).

Please refer to Section 2.7 for further information on uncertainty assessment.

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3.2 OVERVIEW OF THE EXISTING FOREST AREA CHANGES MONITORING SYSTEMS

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3.2.1 Scope of section

This section presents an overview of the existing forest area changes monitoring systems at the national scale in tropical countries using remote sensing imagery.

Section 3.2.2 describes national case studies: the Brazilian system which produces annual estimates of deforestation in the legal Amazon, the Indian National biannual forest cover assessment, and an example of a sampling approach in the Congo basin.

3.2.2 National case studies

3.2.2.1 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 km^2, large enough to cover all of Western Europe. Around 4 million km^2 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, up to 214 Landsat satellite images are acquired around August, and analyzed. Results of the analysis of the satellite imagery are published annually. Spatially-explicit results of the analysis are publicly available (see http://www.obt.inpe.br/prodes/).

The PRODES project has been producing the annual rate of gross deforestation since 1988 using a minimum mapping (change detection) unit of 6.25 ha. To be more detailed, and so as to profit from the dry weather conditions of the summer for cloud free satellite images, the project is carried out once a year, with the release of estimates foreseen in December of that same year. PRODES uses imagery from TM sensors onboard Landsat satellites, sensors of DMC satellites, and CCD sensors from CBERS satellites, with a spatial resolution between 20m and 30m.

PRODES also provides the spatial distribution of critical areas (in terms of deforestation) in the Amazon. As an example, for the period from August 1st, 2007, to August 1st, 2008, more than 90% of the deforestation was concentrated in 87 of the 214 satellite images analyzed.

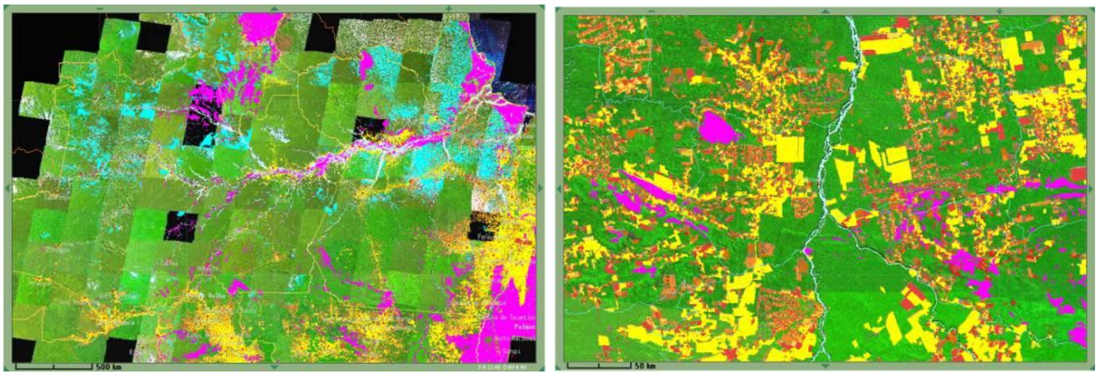
PRODES has quantified approximately 750,000 km^2 of deforestation in the Brazilian Amazon through the year 2010, a total that accounts for approximately 17% of the original forest extent. PRODES is being extended to include reforestation and to cover all Brazilian territory.

Box 3.2.1. 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 Juruena) (~ 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 the operational phase. A geo-referenced, multi-temporal database is produced including a mosaic of deforested areas by States of the Brazilian federation. All results for the period from 1997 to 2011 are accessible and can be downloaded from the INPE web site at: http://www.obt.inpe.br/prodes/.

Since May 2005, the Brazilian government also has the DETER (Detecção de Desmatamento em Tempo Real) system in operation to serve as an almost real-time (every 15 days) alert 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 modelling and visual analysis. Results are publicly available through the following website: http://www.obt.inpe.br/deter/.

To complement PRODES and DETER, a new system, named DEGRAD, was developed in 2008 to monitor forest area changes within forests (forest degradation), particularly burned area. Selective logging was the subject of another project named DETEX. The demand for DETEX emerged after recent studies confirmed that logging annually damages an area as large as the area affected by deforestation in this region (i.e., 10,000-20,000 km2/year). The DEGRAD system will support the management and monitoring of large forest concession areas in the Brazilian Amazon. The DEGRAD system is based on the detection of degraded areas detected from the DETER alarm system. As with PRODES, DEGRAD uses Landsat TM and CBERS data with a minimum mapping unit of 6.25 ha. Degraded areas have been estimated for the Brazilian Amazonia from 2007 to 2010 (http://www.obt.inpe.br/degrad/).

3.2.2.2 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 the 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 during 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 12th biennial cycle was completed by the end of 2011 from digital interpretation of data at 23.5 m resolution with a minimum mapping unit of 1 ha. The details of the data, scale of interpretation, and methodology followed in the wall to wall forest cover mapping over a period of 2 decades in India, is presented in Table 3.2.1.

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 (XII cycle) used satellite data from the Indian satellite IRS P6 (Sensor LISS-III at 23.5 m resolution) mostly from the period between October and December 2008, 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 the 313 LISS-III scenes covering the Indian Territory. For a few cases (e.g., Lakshadweep, where cloud free data for all Islands were not available) the data period was extended to March 2009.

Table 3.2.1. State of the Forest Assessments of India

Assess-ment	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	End 2004	IRS P6 LISS III	23.5 m	1:50,000	digital	67.70
XI	End 2006	IRS P6- LISS III	23.5 m	1:50,000	digital	69.09
XII	End 2008	IRS P6- LISS III	23.5 m	1:50,000	digital	69.20

Satellite data are digitally processed, including radiometric and contrast corrections, and geometric rectification (using geo-referenced topographic sheets at 1:50,000 scale from the 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. Areas with less than 1 ha are filtered (removed).

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 and States/Union Territory 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 XII assessment, 5,729 points were distributed in a stratified random manner over the entire country. The overall accuracy level of the forest cover mapping for 2006 (5 forest classes) was estimated to be 92%.

India classifies its lands into the following cover classes:

Very Dense Forest	All lands with a tree cover canopy density greater than 70%
Moderately Dense Forest	All lands with a tree cover canopy density between 40 -70 %
Open Forest	All lands with a tree cover canopy density between 10 – 40 %
Scrub	All forest lands with a tree cover canopy density less than 10 percent

Nonforest	Any area not included in the above classes

3.2.2.3 Congo basin – example of a sampling approach

Analyses of changes in forest cover at regional to national scales have been carried out by the research community with the involvement of national experts. As one example, a regional exercise was carried out in Central Africa with the participation of international institutions and national experts under the framework of the Observatory for the Forests of Central Africa (OFAC)[107]. For the period 1990 to 2005, a systematic sampling approach using mid-resolution imagery (Landsat) was operationally applied to the entire Congo River basin to accurately estimate deforestation at the regional level, and for large-size countries, at the national level. The survey was composed of 20 × 20 km^2 sampling sites systematically distributed every 0.5° over the whole forest domain of Central Africa, corresponding to a sampling rate of 13.6 % of total area. This resulted in 547 sample sites over the Congo Basin. For each site, subsets were extracted from both Landsat TM and ETM+ imagery acquired in 1990, 2000, and 2005 respectively. The satellite imagery was analyzed with object-based (multi-date segmentation) unsupervised classification techniques.

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 was observed, were 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 was defined spectrally from the imagery (lighter tones in image color composites as compared to dense forests – see next picture).

For Central Africa (with 186 million hectares of forest cover), this exercise led to an estimate of the annual gross deforestation rate at 0.26 ± 0.04 % for the period 2000-2005. For the Democratic Republic of Congo, which is covered by a large number of samples (267), the estimated annual deforestation rate was 0.32 ± 0.05%. Degradation rates were also estimated (gross annual rate: 0.14 ± 0.02 % for the entire basin).

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[107] http://observatoire-comifac.net/index.php

Box 3.2.2. Example of results of interpretation for a sample in Congo Basin

Landsat image (TM sensor) year 1990

Box size: 10 km x 10 km

Landsat image (ETM sensor) year 2000

Box size: 10 km x 10 km

Image interpretation of year 1990

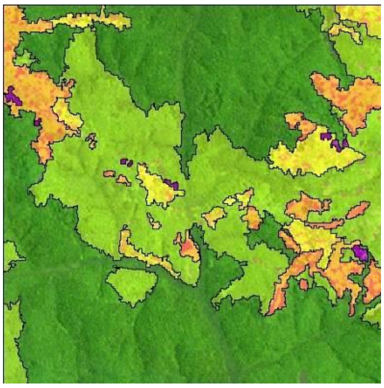
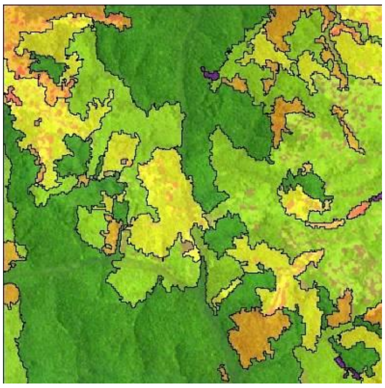


Image interpretation of year 2000



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

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3.3 FROM NATIONAL FOREST INVENTORY TO NATIONAL FOREST GHG INVENTORIES

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3.3.1 Scope of section

Section 3.3 presents two national case studies for forest inventories in tropical countries: the Indian and Mexican national forest inventories. These national forest inventories have been use to report GHG inventories to the UNFCC

India has long term experience conducting forest inventories at divisional / district levels for estimating growing stock of harvestable timber. With a view to generating a national level estimate of growing stock in a short time, and coordinating with the biennial forest cover assessment based on satellite imagery, a new National Forest Inventory (NFI) was designed in 2001, and has been used operationally up to the latest national forest inventory report (Forest Survey of India, 2009). The results of past Indian national forest inventories were used in the Initial National Communication to the UNFCCC produced in 2004. The Second National Communication being finalized now has used results of the new NFI, and the supplementary inventory completed during 2008-2009, to estimate missing components of forest biomass. These two results have been integrated with spatial data on forest cover monitoring to estimate the national greenhouse gas emissions from the forestry sector.

The Mexican inventory of greenhouse gas (GHG) emissions from the land-use sector involved integration of forest inventory, land-use and soil data in a GIS to estimate the net flux of GHGs between 1993 and 2002. In the last decade, Mexico has gathered national information, including systematically collected spatially explicit data that allow for a more reliable GHG inventory (de Jong et al. 2010). Additionally, a national database of wood densities and allometric equations to convert inventory data to biomass and volume was generated. The results have been used in Mexico’s national GHG inventory where national emissions were reported up to the year 2002, at TIER 2 in the third communication, and up to 2006 (between Tier 2 and 3) in the fourth communication (INE-SEMARNAT, 2006, 2009).

3.3.2 Introduction to forest inventories in tropical countries

Traditionally, forest inventories in several countries were done to obtain a reliable estimate of the forest area and growing stock of wood for overall yield regulation purposes. 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 on the growing stock of wood by diameter class, the number of trees, as well as the composition of species. Repeated measurement of permanent sample plots also provides the changes in the forest growing stock/ biomass.

A number of sampling designs have been used to conduct inventories, the most common of which are systematic sampling, stratified random sampling, and cluster sampling. The sampling designs, size and shape of the sample plots, and the accuracy levels have depended on the situation of the forest resource, the time frame available, the allocated budget, and availability of skilled human resources.

In the developing regions of the world, several countries (Myanmar[108], Malaysia, Indonesia, Bangladesh, Sri Lanka) undertook one time forest inventories for projects, usually at the sub-national level, and some at the national level. There are, however, a few countries like India and China that are conducting national forest inventories on a regular basis, and have well established national institutions to conduct them.

Traditional Forest inventories in India

India has long term experience conducting forest inventories at the divisional / district levels (which include a forest area of approximately 1,000 km^2), mainly for estimating the growing stock of harvestable timber needed for the preparation of operational plans (i.e. called a Working Plan). The first working plan of a division was prepared in the 1860s, and then gradually extended to other forest areas. The methodology for preparation was refined, and quality improved with the availability of better maps and data. These inventories followed a high intensity of sampling (at least 10%), but covered only a limited forest area (about 10 to 15%) of a division supporting maturing crops, where harvesting would occur over a plan period of 10 to 15 years (Pandey 2008).

The practice of preparing a Working Plan for operational purposes continues even today (undertaken by provincial governments), but the scale of harvest has been greatly reduced due to increasing emphasis on forest conservation. With the availability of modern inventory tools and methods, a few provinces have begun to inventory the total forest area of their divisions with low intensity sampling, mainly to assess the existing growing stock for sustainable forest management (SFM), in addition to timber harvest.

In the Indian case, almost all the forests of the country are owned and managed by provincial governments. The federal government is mainly responsible for formulating policies, strategic planning, enacting laws, and providing partial financial support to provinces. The inventory data of the working plans do not contain adequate information to estimate growing stock, and other parameters of the forest resource at the province or national level.

3.3.3 Large scale forest inventories: 1965 to 2000

A relatively large scale comprehensive forest inventory was started by the federal government with the support of the FAO and UNDP in 1965, using a statistically robust approach and aerial photographs, under a project named Pre-Investment Survey of Forest Resources (PIS). The inventory was aimed at strategic planning with a focus on assessing wood resources in less explored forests of the country, for establishing wood based industries with a low intensity sampling (0.01%). The PIS inventory was neither linked to Working Plan preparation, nor were its data used to supplement local level inventories. The PIS was subsequently reorganized into a national forest monitoring system and a national institution known as the Forest Survey of India (FSI). FSI was created in 1981 with the basic aim of generating continuous and reliable information on the forest resource of the country. During the PIS period, about 22.8 million ha of the country's forests were inventoried (Forest Survey of India 1996a). After the creation of

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[108] Shutter H (1984) National Forest Survey and Inventory of Burma (unpublished), input at 2nd Training Course in Forest Inventory, Dehradun, India

the FSI, the field inventory continued with the same strength and frequency as the PIS, but with modified design. The total area inventoried by the year 2000 was about 69.2 million ha, which includes some areas that were inventoried twice. Thus, more than 80% of the 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΄ minute longitude by 2½΄ minute latitude) 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.

3.3.3.1 National forest inventories post 2001

To generate a national level estimate of growing stock in a short time, and coordinate with the biennial forest cover assessment based on satellite imagery, a new National Forest Inventory (NFI) was designed in 2001. Under this program, the country was divided into 14 physiographic zones based on features including climate, soil and vegetation. The method involved sampling 10 percent of the approximately 600 civil districts, representing the 14 different zones in proportion to their size. About 60 districts were selected to be inventoried in a two year 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 the first cycle will be combined with the second and subsequent cycles. The random selection of the districts is without replacement; hence, each time new districts are selected (Forest Survey of India 2008).

3.3.3.2 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, are treated as forest. For each selected district, Survey of India topographic sheets of 1:50,000 scale were divided into 36 grids of 2½ ΄ (minute longitude) by 2½΄ (minute latitude). Further, each grid was divided into 4 sub-grids of 1¼΄ by 1¼΄ forming the basic sampling framework. Two of these sub-grids were then randomly selected for establishing sample plots from one end of the sheet, and then systematic sampling was followed for selecting other sub-grids. The intersection of diagonals of such sub-grids was marked as the center of the plot at which a square sample plot of 0.1 ha was laid out to conduct the field inventory (Figures 3.3.1 and 3.3.2).

Figure 3.3.1. Selected districts under India's national forest inventory.

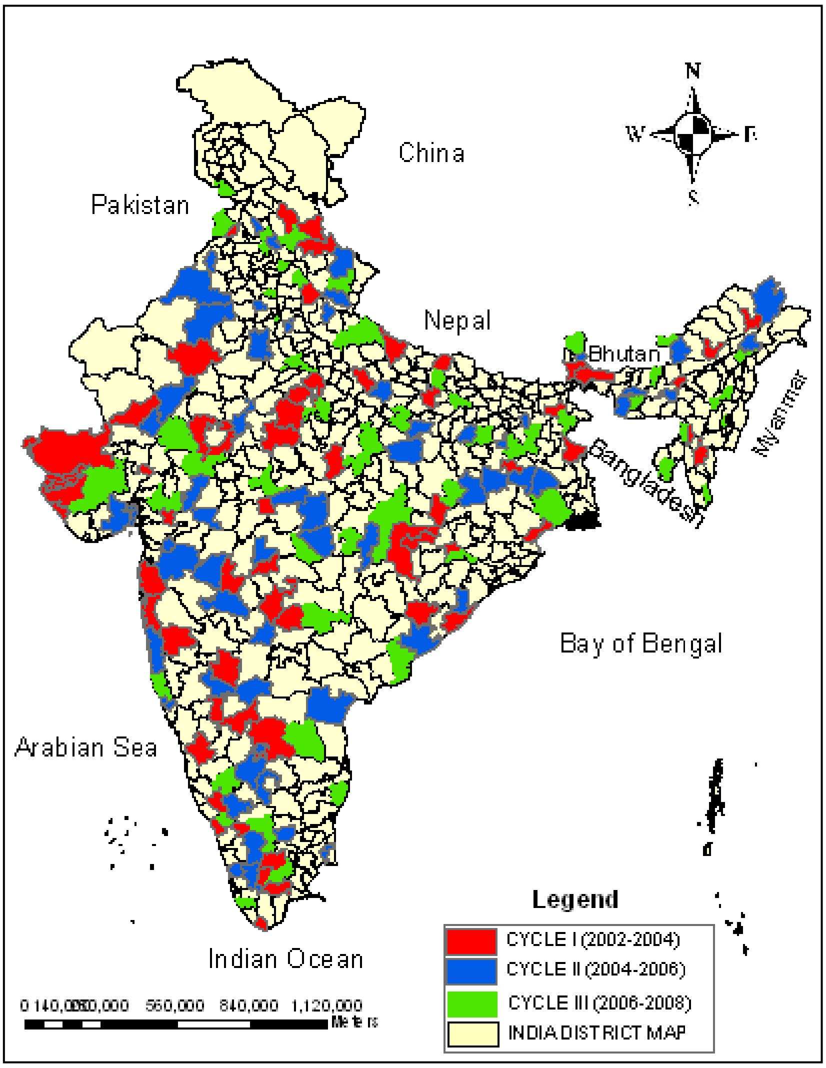
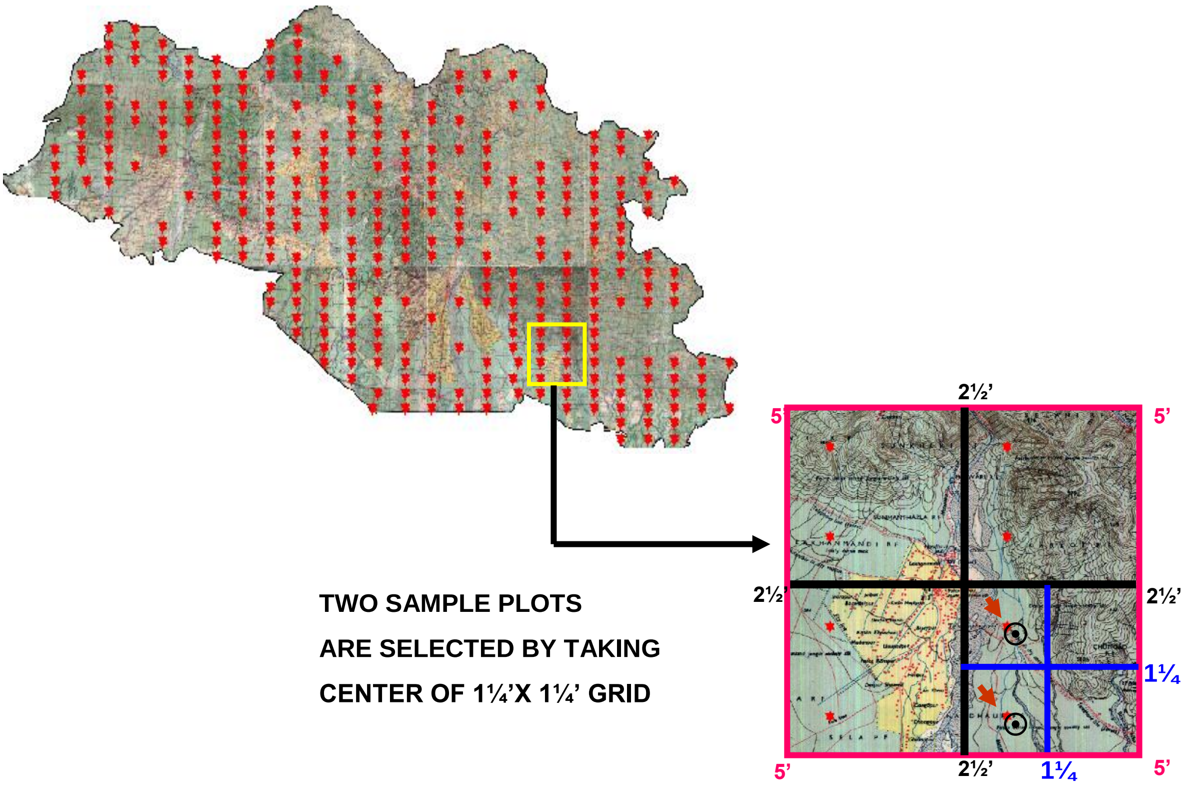


Figure 3.3.2. Forest inventory points in one of India’s districts.



Diameter at breast height (dbh, 1.37 m) of all trees above 10 cm in the sample plot, and height as well as crown diameter of trees standing in one quarter of the sample plot were measured. In addition, legal status, land use, forest stratum, topography, crop composition, bamboo, regeneration, biotic pressure, and species name falling in forest area, were also recorded. Two 1 m^2 sub plots were laid out at opposite corners of the sample plot to collect litter/ humus and soil carbon samples (from a 30 cm x 30 cm x 30cm pit). Further, nested 3 m x 3 m and 1m x 1 m quadrates were laid at a 30 m distance from the center of the plot in all four corners for enumeration of shrubs and herbs for biodiversity assessment (Forest Survey of India draft 2008).

In two years, about 7,000 sample plots representing different physiographic zones in the 60 selected districts were established and inventoried. The field operations of the NFI were executed by the four zonal offices of the FSI, located in different parts of the country. About 20 field parties (each comprised of one technician as a leader, two skilled workers, and two unskilled workers) carried out the field inventory for at least eight months of the year. During the four rainy months, the field parties carried out data checking and computer data entry at the zonal headquarters. The data were sent to the FSI headquarters for checking and processing. After manual checking of the sample data in a random way, inconsistency checks were carried out using software, and then, under the supervision of senior professionals, the data were processed to estimate various forest resource parameters .

For estimating the volume of standing trees, the FSI developed volume equations for several hundred tree species growing in different regions of the country (Forest Survey of India, 1996b). These equations were used to estimate the wood volume of the sample plots. Equations were developed for the volume of trees measured above 10 cm dbh, however, trees below 10 cm dbh were not measured and their volumes, not estimated.

In addition, for the trees above a 10 cm dbh, the volume of the main stem below a 10 cm diameter, and branches below a 5 cm diameter, were not measured. Thus, the existing volume equations underestimate the biomass of trees species. The aboveground biomass of other living plants (herbs and shrubs) also was not measured.

3.3.3.3 Inventory for missing components of the forest biomass

As mentioned in the previous section, the current national forest inventory (NFI) does not generally measure the total biomass of trees, herbs and shrubs, or deadwood. Therefore, a separate nationwide exercise was undertaken by FSI starting in August 2008 (FSI draft 2008) to estimate the biomass of the missing components. In this exercise, there were two components, and both involved destructive sampling.

One component was the measurement of individual trees to estimate the volume of trees between 0-10cm diameter at breast height (dbh), and to estimate the volume of branches below 5 cm, and stem wood below 10 cm, for trees above a 10 cm dbh. About 20 tree species in each physiographic zone were covered in this exercise. In all, about 100 tree species were covered at the national level. The trees and their branches were cut and weighed in a specified manner to measure the biomass. New biomass equations were developed for the trees species below a 10 cm dbh. For the trees above a 10 cm dbh, the additional biomass measured through this exercise was added to the biomass of tree species of corresponding dbh, whose volume and biomass were already estimated during the NFI. This provided the total biomass of the trees starting at a diameter of 0 cm.

In the second component, sample plots were laid out for measuring the volume of deadwood, herbs, shrubs, climbers, and litter. Due to time limitations, only a minimum number of samples plots had been established. In all, there are 14 districts in the country, that is, one district in each physiographic zone. While selecting districts (already inventoried under NFI), due care was taken to ensure that all major forest types (species) and canopy densities were properly represented. About 100 sample points were established in each district. At the national scale, there were about 1,400 sample points. The geo-coordinates of selected sample points in each district were sent to field parties to carrying out the field work. In a stratum based on type and density, about 15 sample plots were selected, resulting in a permissible error of 30%. At each sample plot, three concentric 5 m x 5 m plots were established for dead wood, 3 m x 3 m plots for shrubs, climbers, and litter, and 1 m x 1 m plots for herbs (Forest Survey of India-draft 2008). The deadwood collected from the sample plots was weighed in the field. Green weight of the shrubs, climbers, and herbs cut from the ground was also measured, and later converted into dry weight by using suitable conversion factors. This exercise resulted in the calculation of the biomass of deadwood and litter, as well as the biomass of the other non–tree vegetation excluded from the NFI.

3.3.3.4 National greenhouse gas inventory from forestry land-use

The NFI, when combined with supplementary inventory, provided the total living biomass aboveground, and the measurements of deadwood and litter. Analysis of the soil samples collected during the NFI provided the soil organic carbon for different forest types and densities. For belowground biomass of root systems, default IPCC values were used with exceptions for a few species for which studies were conducted in India in the past by forestry research institutions to estimate root biomass. By using suitable conversion factors, carbon in each component, and then forest carbon stock on per unit area for each forest type and density, was estimated. Comparisons of two spatial datasets of forest cover by type and density taken at different times helped to generatea forest land-use change matrix. Integrating the change matrix with values of carbon stock per unit area of forests resulted in the generation of GHG emissions and removals (Indian Network for Climate Change Assessment 2010).

3.3.3.5 Estimation of costs

The total number of temporary sample plots laid out in the forests of 60 districts is about 8,000, and measurements are completed every 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 per sample plot comes to about USD$ 158.00, and includes travel to the sample plots, field measurement (including checking by supervisors), and field preparation, equipment, designing, data entry, processing etc.

The additional cost for estimating the missing components of biomass has been worked out to be about USD $52 per plot. This cost would be greatly reduced if the exercise of obtaining additional measurements were combined with regular activities of the NFI. Moreover, developing biomass equations for trees below and above 10 cm dbh is a one-off exercise, and will not result in future costs.

3.3.4 GHG emissions in Mexico from land-use change and forestry

3.3.4.1 Introduction

The Mexican inventory of greenhouse gas (GHG) emissions from the land-use sector involved integration of forest inventory, land-use and soil data in a GIS to estimate the net flux of GHGs between 1993 and 2002 using the IPCC 1996 guidelines, and between 1990 and 2006, using the 2006 guidelines.

In the last two decades, Mexico has had two national forest inventories, one establishing about 16,000 plots of 1000 m^2 between 1992 and 1994, in which all aboveground living biomass pools were measured or estimated. Dead standing trees and tree stumps were included, but no data were collected on fallen dead wood or soil organic matter. In 2004, a new forest inventory was initiated, establishing a network of about 25,000 permanent sampling points, each comprised of four, 400 m^2 plots (1,600 m^2 in each point). Between 2004 and 2008, more than 22,000 points were measured, with data collecting procedures similar to those used in the 1992-1994 inventories. Re-measurement of the 20% of the points each year started in 2009, and from that year onward, all carbon pools were systematically measured in each point, according to IPCC standards. Soil samples were collected up to 30 cm, and dead fallen wood was measured applying the line-transect sampling procedure. In 2009, about 4,700 were revisited, and a similar number in 2010.

The data from both inventories have been used to estimate the GHG emissions in the land-use sector. The 1992-1994 data were used in the third communications (see de Jong et al. 2010). The project involved a comprehensive effort to calculate changes in land-use by integrating land-use maps from 1993 and 2002, carbon stocks derived from the forest inventory, and separate soil carbon data. These spatially explicit data were combined with emission factors derived from national governments and specialized literature sources to estimate the net flux of GHGs. The project also aimed at identifying and quantifying the sources of uncertainty to provide direction for ongoing and future data collecting activities.

The results served as a basis to define what additional information is required in order for Mexico to enter into international forestry based mitigation efforts, such as REDD+. The project was part of the national GHG inventory of Mexico where national emissions were reported up to the year 2002 (INE-SEMARNAT, 2009).

3.3.4.2 National Forest Inventory

National forest inventory data are available from 1992-1994, comprising about 16,000 sites of 1000 m^2, established in conglomerates of up to 3 sites (Figure 3.3.3a). A systematic approach was used to distribute the conglomerates. Data collected in each site included individual tree diameter (DBH = 1.30 m), total and merchantable height and species of all trees > 10 cm DBH, cover of shrub and herbaceous vegetation, and counts of natural regeneration of trees (SARH, 1994).

In 2004, a newly designed National Forest Inventory was developed, and between 2004 and 2007, about 25,000 georeferenced permanent points were established, of which about 22,000 points were measured (Figure 3.3.3b); each point has 4 sites, 400 m^2 in size, with a total of 1,600 m^2 per point (Figure 3.3.4). From 2008 onward, about 20% of the points were remeasured annually (Figure 3.3.5); about 50 percent of all points were re-measured in 2008, 2009 and 2010. As of 2009, all major Cpools are included in the remeasurements, including fallen dead wood, litter, and soil organic matter. A total of 1,300,000 trees were measured from 2004-2007. As of 2009, all trees are individually labeled.

A database of published allometric equations was generated to convert inventory data to biomass and volume. Equations were developed at the level of species, genera, groups of species with similar architecture, and ecosystems, covering more than 90% of all individual trees measured between 2004 and 2007. For the remaining trees, generic equations were created. Volume equations and wood density data have been used to create biomass expansion factors (BEF). These factors are used to convert reported harvesting volumes to total biomass. As part of the reporting requirements for the 2010 Forest Resource Assessment, coordinated by the FAO, a 2007 biomass density map was generated based on a preliminary 2007 land use and land cover map (INEGI, unpubl.), and the 2004-2008 inventory data (Figure 3.3.6).

Figure 3.3.3a. Distribution of the 1992-1994 Forest Inventory plots in Mexico (approx. 6,500 plots, 16,000 sites), based on precipitation class.

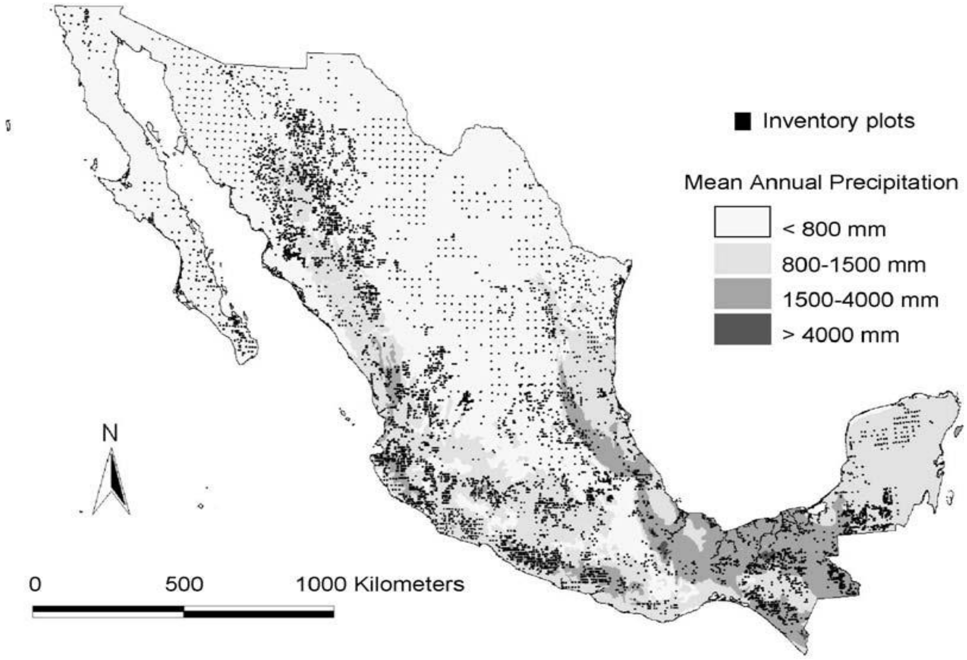


Figure 3.3.3b. Distribution of the 2004-2008 National Forest and Soil Inventory plots in Mexico of (approx. 25,000 plots; 84,000 sites.), and plots remeasured in 2009.

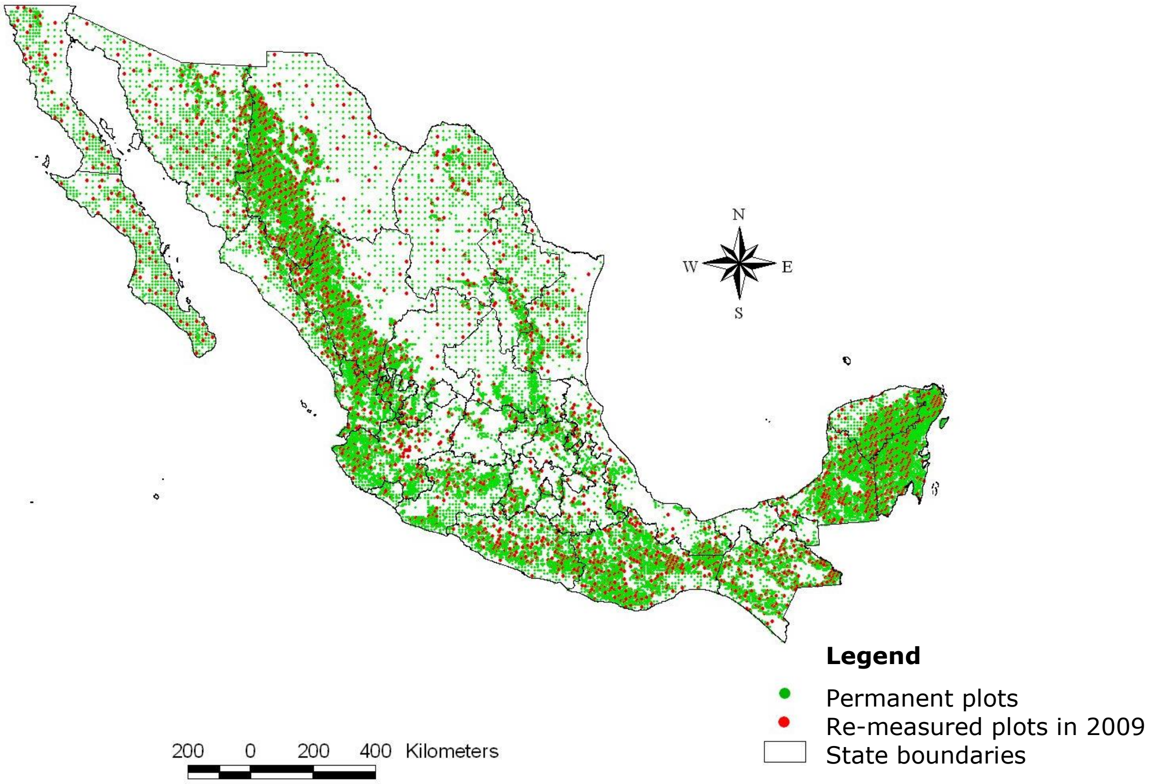


Figure 3.3.4. The inventory plot design with four, 400 m2 sites in each plot, and the full circle encompassing 1 ha.

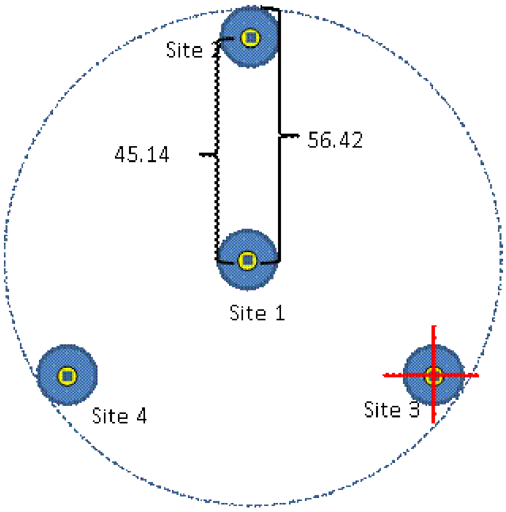


Figure 3.3.5. Each year, 20% of the permanent plots are resampled systematically.

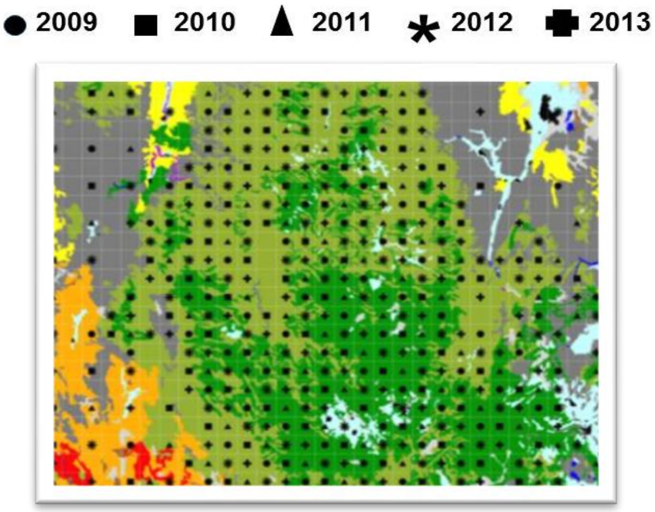
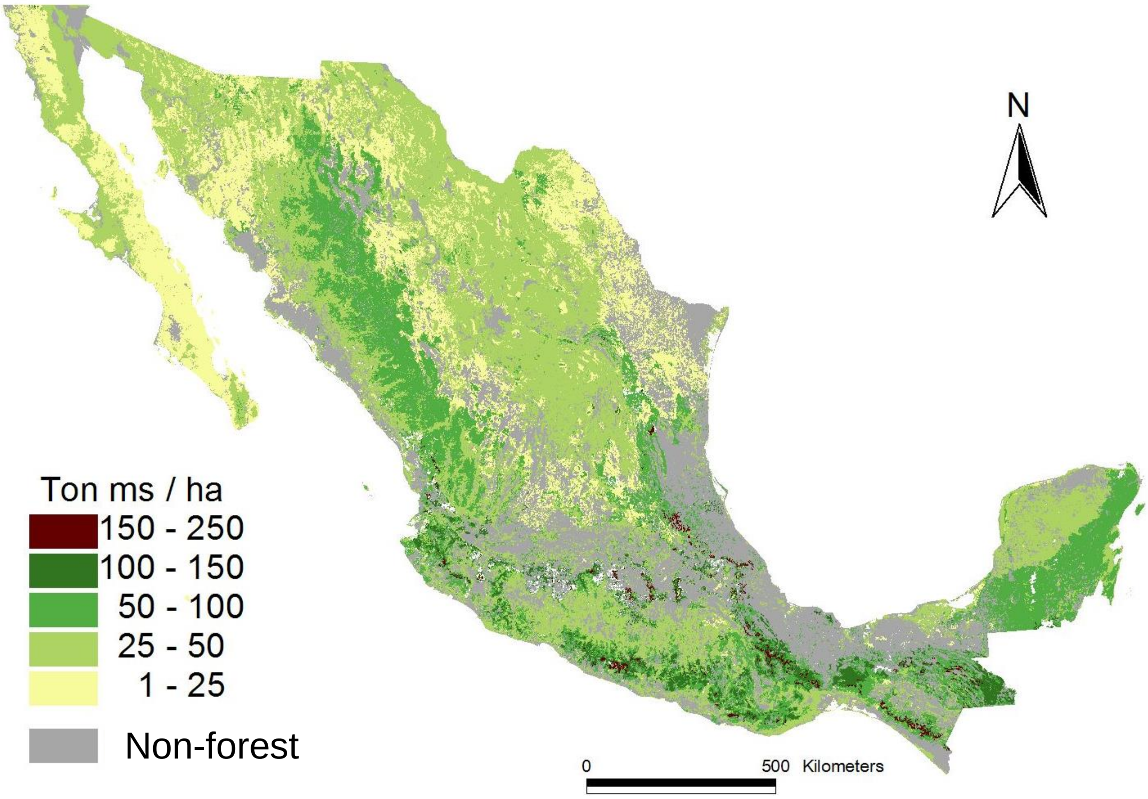


Figure 3.3.6. Biomass density map (in T dry matter) for 2007, derived from INEGI vegetation map (2007), and INFyS 2004-2008 plot data.



3.3.4.3 Sources of uncertainty

The main sources of uncertainty include a lack of integrated soil and biomass data, and information and data on the impacts of various management practices on biomass. Key factors have been identified to improve GHG inventories, and to reduce uncertainty.

3.3.4.4 Reporting to the UNFCCC

This section presents the Mexican inventory of greenhouse gas (GHG) emissions from the land-use sector. It involved the integration of forest inventory, land-use and soil data in a GIS to estimate the net flux of GHGs between 1993 and 2002.

In Mexico, the LULUCF sector was considered the second source of GHG emissions after fossil fuel consumption, with a total of 112 $TgCO_2\ y^{-1}$ (INE-SEMARNAT, 2001). However, this estimate was based on default and project-based data from the literature. Based on the 1992-1994 inventory data, default expansion factors, national land use and land cover maps from 1993 and 2002, and forestry statistics, GHG emissions have been estimated for the LULUCF sector in Mexico from 1993 to 2002, and have been reported up to the year 2002 in the third national communication to the UNFCCC (INE-SEMARNAT, 2006).

The methodology we used follows the approach proposed by the IPCC (mainly IPCC, 1997; with adjustments according to Penman et al. (2003). This approach is based on assessing changes in biomass and soil carbon stocks in forests and forest-derived land uses due to human activities, and relies on two related premises: (1) the flux of carbon to or from the atmosphere is assumed to be equal to changes in carbon stocks in existing biomass and mineral soils, and (2) changes in carbon stocks can be estimated by establishing rates of change in area by land-use and related changes in C stocks, and the practices used to carry out the changes. An update of the national GHG inventory was developed for the years 1990 to 2006, published in the fourth national communications (INE-SEMARNAT 2009), that is based on the IPCC 2006 guidelines. This inventory used the National Forest and Soil Inventory 2004-2008 data, nationally developed emission factors, national land-use and land cover maps of 1993, 2002 and 2007, and available national statistics.

3.3.5 Key references for Section 3.3

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3.4 COMMUNITY FOREST MONITORING

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3.4.1 Rationale for community-based inventories.

Forest land in developing countries is increasingly being brought under community management under programs such as Joint Forest Management, Community-based Forest Management, Collaborative Management, etc., more generally called Community Forest Management (CFM). This movement has been stimulated by the recognition in many countries that Forest Departments (FD), which are nominally responsible for management of state-owned forest, do not have the resources to carry out this task effectively. Rural people, whose livelihoods are supplemented by, or even dependent on, a variety of forest products such as firewood and fodder, foods and medicines, have the potential knowledge and human resources to provide effective management capacity to take care of the forest resources when the FD cannot. These actors are not only forest peoples with indigenous entitlements or customary rights to the forest lands, but countless rural communities adjacent to forest areas with accumulated knowledge of them.

The UNFCCC recognizes the special position that 'indigenous and forest peoples' have in REDD+, having repeatedly called for the full and effective participation of indigenous peoples and local communities in REDD+ since the first decision on REDD+ was made by the COP at its 13th session in Bali, December 2007. The interpretation of *full and effective* is left to the individual countries implementing REDD+, but specific reference to monitoring and reporting is made in paragraph 3 of Decision 4/CP.15. In paragraph 72 of Decision 1/CP.16 countries are requested *when developing and implementing their national strategies or action plans, to address, inter alia, the drivers of deforestation and forest degradation, land tenure issues, forest governance issues, gender considerations and the safeguards […], ensuring the full and effective participation of relevant stakeholders, inter alia indigenous peoples and local communities*. This issue is referred to directly in one of the safeguards. Developing countries implementing REDD+ therefore have to *promote and support* (paragraph 2 of Appendix I) this participation and provide information on how this is *addressed and respected* (paragraph 71(d)). There is increasing evidence that communities can be effectively engaged in different aspects of monitoring (Box 3.4.1; Danielsen et al. 2011; Larrazabal et al. 2012; Hawthorne & Boissière 2014).

One component of CFM is to mitigate the over-exploitation which leads to degradation and loss of biomass. The CFM approach is to establish formal systems between communities and FDs in which, usually, communities receive a legalized right to controlled use of forest products from a given parcel of forest, and in return formally agree to protect the forest and manage it collectively. Different approaches to CFM are found in different countries. In Nepal and Tanzania, most of the forest parcels are relatively small, from 25 to 500 hectares, being managed by groups of 10 to 100 households on the basis of agreed off-take of firewood, fodder etc. In Mexico, forest areas may be from 300 to 15,000 hectares and are sometimes managed for timber. In the Amazon, much larger areas may be restituted to indigenous groups, and managed essentially for conservation. The conditions may vary widely - in Mexico for example, the majority of the forest area is legal property of communities, while in most African countries it is the property of the state.

We introduce here the idea that communities involved in CFM can carry out forest surveys as a part of their forest management, when they have a substantive interest in it. Note that this review of community forest monitoring is limited woody biomass, particularly AGB (above ground biomass carbon); it does not deal with soil carbon.

There are a number of reasons within REDD+ programmes why communities may need to be involved in forest surveys:

- For participation in REDD+, it may be a requirement to gather detailed information on carbon stock changes at the community scale, since although forest area change can be measured using remote sensing, changes in biomass density (degradation and forest enhancement) cannot be reliably established without ground level measurements
- Community monitoring may supply valuable information on the drivers of deforestation and degradation and on the impacts of projects and programmes intended to mitigate these.
- Local information on performance with regard to safeguards under REDD+ may be required from communities.
- Data from community-based forest surveys could feed into and densify national level databases, thus supporting and strengthening MRV for REDD+ and other forest reporting systems
- The surveys may also support other forms of monitoring, for example by providing ground level data against which to calibrate remote sensing data; it may be particularly useful in identifying different forest types which are difficult to distinguish in satellite imagery
- Community monitoring may in some cases form the basis for benefit-sharing in REDD+.

The interest for communities to be engaged in forest resource surveys can extend beyond REDD+ issues (see Sect. 3.4.9). In particular, stand out:

- PES (Payment for Environmental Services) projects for other environmental services – notably biodiversity services, usually also require reliable, detailed measurements of environmental indicators at community level.
- Certification schemes, where communities are engaged in certified timber or NTFP production, which require intensive monitoring and verification.
- And importantly, engagement in monitoring may strengthen the communities´ forest management practices, by providing feedback to themselves on management outcomes.

A number of initiatives on community-based monitoring have shown it to be both feasible and beneficial, for example the CCA project which has demonstrated that through well-designed and implemented training programmes and ongoing back-up support, community-based forest monitoring teams can take and record measurements for accurate and precise estimates of forest carbon stock changes (Box 3.4.1). The CCA study suggests that from a climate change perspective, communities should be involved in forest monitoring, because not only will this enrich the data used for estimating carbon stock changes and increase transparency, it will also enhance the sustainability of REDD+ activities, as communities will have a better understanding of what must be done to ensure future REDD+ payments.

There are significant degrees of intensity or degree of the community involvement in forest monitoring, sometimes summarised as a 'Participation Ladder".

At the minimal level of participation, there is only externally-driven monitoring, professionally executed, and community inputs are limited to their local knowledge about the area. The next level is externally-driven monitoring but with local data collectors who will be recruited to help locate sample sites and collect local data in UNFCCC protocols.

Next there is collaborative monitoring with external data analysis and interpretation, but with some local inputs on content and criteria probably for the social monitoring and safeguards. The fourth level is collaborative monitoring which also engages with local data capture, data interpretation, and local applications of the monitored data (for community purposes). Finally the strongest participation is in autonomous local monitoring, where there is also administrative autonomy and the capacity to change the monitoring systems.

Box 3.4.1 IGES Community Carbon Accounting (CCA) Project

Together with its partners, the Institute for Global Environmental Strategies launched the Community Carbon Accounting (CCA) Project with the intention of developing and testing approaches for engaging communities in forest carbon stock change estimation. With funding from the Ministry of Environment of Japan and the Asia-Pacific Network for Global Change Research, the CCA Project is being implemented at sites in Cambodia, Papua New Guinea (PNG), Indonesia, Laos and Vietnam according to local contexts, opportunities and needs.

The CCA Project provides the following observations for REDD+ project developers and for governments in the process of establishing their national forest monitoring systems (NFMS):

- **Communities can take accurate forest measurements**. With proper training, community teams can take and record forest measurements to provide accurate and precise forest carbon stock estimates that fall well within the range of uncertainty for estimates in similar forest types from professional surveys.

- **Community teams retain the skills they have learnt**. In January 2012, Project partners observed a community forest monitoring team in Cambodia which had received training one year earlier on forest sampling and measurement, and they demonstrated that they had retained the knowledge and skills from this training. Local people who participate in a well-designed training programme can be relied upon for future forest assessments.

- **The training of trainers is critical**. The training of communities on forest measurement is not a simple task. Literacy rates may be low and communities may have received misinformation on issues such as carbon trading. In all Project countries, a structured training of trainers (ToT) was organised to ensure trainers possessed the necessary knowledge on forest carbon accounting and effective techniques for training communities on forest sampling.

- **Communities can do more than is often assumed**. Projects engaging communities in REDD+ should not have rigid views on what communities can and cannot do. Some communities may have members who are competent with and own computers. In such cases, the responsibility for data entry could be given to the community. In participating villages in Jogjakarta Province, Indonesia, the communities were trained in the use of spreadsheets and have taken on the role of data entry using the spreadsheets created for them.

- **The aim should be self-reliant community-based forest monitoring teams**. The aim should be self-reliant teams that can be depended upon for estimation of forest carbon stocks according to pre-determined monitoring intervals. The community forest monitoring teams should thus own the equipment necessary to set up and measure sample plots.

For further information on the CCA Project, see:
http://www.iges.or.jp/en/natural-resource/forest/activity_cca.html

Procedures and protocols for the involvement of local communities in REDD+ activities are within the purview of individual national governments. Political ideologies, land ownership and tenure rights, competing claims on forest resources (e.g. commercial logging operations) all contribute to the variability of conditions that make a single solution impossible. It seems likely that the requirements for large scale data collection, for example for REDD+, will necessitate the involvement of local communities in most countries, if only to reduce the cost of the surveys (see 3.4.5). However, if community monitoring is to be integrated in a formal way into national data systems it is clear that a standard protocol would have to be developed at national level and communities would have to follow this, at least for a minimum of key variables and indicators (CIGA, 2014). Although many manuals for community monitoring are available (see Box 3.4.4), no country has yet developed a national protocol for this. The material presented here is intended to support governments and other agencies who are looking to engage the effective participation of indigenous people and local communities in monitoring and reporting, as requested by the COP through its decisions on REDD+.

3.4.2 How communities can make their own surveys

Forest surveying is usually considered a professional activity requiring specialized forest education. However, it is well established already that local communities have extensive and intimate knowledge of ecosystem properties, tree species distribution, age distribution, plant associations, etc. needed for inventories. There is growing evidence that local people managing their land, even with very little professional training, can make quite adequate and reliable stock assessments (Larrazábal et al 2012; Skutsch (ed.) 2011). In the Scolel Te project in Mexico (Plan Vivo, n.d.), for example, farmers have for many years made their own measurements, both of tree growth in the agroforestry system and of stock increases in forests under their protection, and they receive (voluntary market) payment on the basis of this.

The methodologies for forest surveying that are available in the form of community manuals (Box 3.4.4) are all based on procedures recommended in the IPCC Good Practice Guidance, but structured in such a way that communities can carry out the steps themselves without difficulty. Intermediary organizations (usually NGOs, also district FD agencies or local consultants) will certainly be required to support some of the tasks, especially the training and the maintenance or upgrading of equipment. But such intermediary organizations are often already present and assisting communities in their forest management work. Much of the work in forest surveying, at least regarding above-ground biomass, is simple and easily learned. It can be carried out by people with very little formal education, working in teams. As all the manuals demonstrate, tree measurements are made using standard equipment such as diameter tapes or callipers, and clinometers. What differs between the manuals is the way in which data is recorded. Although data can always be recorded using paper forms, increasingly hand-held computers/PDAs (personal digital assistants), Smartphones or Tablets with in-built GPS functionality are being employed. These can be operated by people with only primary education, with suitable training and appropriate support. The benefit of this technology is that it allows the recording of plot measurement data in the PDA to be combined with the maps, aerial photos or satellite images that are visible on-screen and linked to the geo-positioning from the GPS. Rural communities almost everywhere are familiar with mobile phones, and find the step to PDAs or Smartphones quite easy.

Some key activities need to be supervised by the intermediaries with understanding of statistical sampling and who can maintain ICT equipment. Many field offices of forestry organization or local NGOs are able to provide such supportive services. To institutionalize community forest surveys, the intermediaries first need to be trained in the methodology. The intermediaries would then train local communities to carry out many of the field survey steps, and they would backup the process at least in the first few years of the survey activities. Certain activities, such as laying out the permanent sample plots, need expertise, but once they are learnt and established, measurements can be made by trained people in the community without assistance. Hence there will be higher costs in the initial years, but these should fall rapidly over time, so long as the trained people remain in the community. See Tables 3.4.1 and 3.4.2 for an overview of the steps involved in this process for the intermediaries and the communities, respectively.

Table 3.4.1.Tasks requiring input from intermediary.

Task	Who?	Equipment	Frequency	Description and comments
1. Identify forest survey team (4 to 7 members)	Intermediary in consultation with community leaders		At start	Need to include people who are familiar with the forest and active in its management; at least some must be literate/numerate. Ideally the same people will do the forest survey work each year so that skills are developed and not lost. [109]
2. Programming PDA with base map, database & C calculator	Intermediary trainers	PDA /smart phone, internet for (geo-locatable) images	Once, at start of work	Aerial photos, satellite images, stereo pairs, Google Earth, or any geo-referenced image /map of suitable scale that can be scanned and entered into the PDA for use as the base map. [110]
3. Map boundaries of community forest	Community, with intermediary assistance	PDA/smart phone with GPS, GIS. Geo-referenced image (e.g. Google Earth)	Once, at start of work	Boundaries of many community forests are known to local people but not recorded on formal maps or geo-referenced. Usually begin with sketch-mapping (without a base map) of the important boundaries, sites and areas for the community, including: forest degradation areas, areas of invasion and zones of conflict, historical land cover and land use changes. Followed by marking onto the geo-referenced images, and then 'walking the boundaries' (and sites) with PDAs and GPS operated by the local team to track and mark the boundaries on the base map.
4. Identify and map any important forest strata	Community with intermediary assistance	PDA/smart phone with GPS, GIS, Geo-referenced image	Once, at start of work	Communities know their forests well. This step is best carried out by first discussing the nature of the forest and confirming what variations there may be within it (different species mix, different levels of degradation, etc.). These can first be sketch-mapped (Task 3); zones can then be mapped by walking their boundaries with the GPS.
5. Pilot survey in each stratum to establish number of	Community with intermediary assistance	Tree tapes or calipers, clinometers		The pilot survey is done with around 15 plots in each stratum. Measuring the trees in these plots could form the training exercise in which the intermediary first introduces the

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[109] Attention must be given to ensuring transparency within the community for the whole process. There is always potential for some inequitable distribution of the benefits from the carbon payments, especially if they are cash payments.

[110] The database format can be downloaded from the K:TGAL website (See Box 3.4.4 below) into a PDA, as can the carbon calculator.

sample plots				community forest survey team to measurement methods.
6. Setting out permanent plots on map	Intermediary	Base map, calculator	Once, at start	This requires statistical calculation of number of plots needed, based on the standard error found in the pilot measurements. [111] Plots are distributed systematically and evenly on a transect framework with a random start point.
7. Locating and marking sampling plots in the forest	Community with intermediary assistance	Map of plot locations, compass, GPS, tape measure, marking equipment	Once, at start	Community team stakes out the centres of the plots in the field by use of compass and measuring tape. GPS readings are recorded, and the centre of the plot is permanently marked (with paint or plate on a ventral tree trunk). Each plot is given an identification code and details (identifying features) entered into the PDA
8. Training community team how to measure trees in sample plots	Intermediary		+/- 4 days first time; 1 day for each of the next 3 years	This task could be fulfilled while carrying out task 5. The task involves listing and giving identification codes to the tree species found in the forest. It is expected that the community will be able to function independently in this task after year 4.
9. Identification of suitable allometric equations & programming into the PDA	Intermediary		Once, at start	The program for the PDA contains default allometric equations. [112] If local ones are available, these may be substituted, which will give greater accuracy.
10. Downloading from the PDA of forest inventory data & forwarding to registration	Intermediary			The PDA is programmed [113] to make all necessary calculations and produce an estimate of the mean of the carbon stock in each stratum, with confidence levels (the default precision is set at 10%). These data need to be transferred to more secure databases for year-to-year comparisons and for eventual registration.
11. Maintaining PDA				PDAs require re-charging on a daily basis and minor repairs from time to time. It is anticipated that an intermediary would have several PDAs and would lend these to communities for the forest inventory work (around 10 days per community per year).

Table 3.4.2. Tasks that can be carried out unaided by the community team, after training.

Task	Equipment	Frequency	Description and comments
Measure dbh (and height, if required by local allometric equations) of all	Tree tapes or calipers, clinometers	Periodically, e.g. annually	During the first year, fairly complete supervision by the intermediary is advisable, but in subsequent years a short refresher training will be sufficient, see

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[111] A tailor-made program for this is downloadable from the K:TGAL website and can be operated on a PDA

[112] From the K:TGAL website.

[113] Ditto.

trees of given minimum diameter in sample plots			above, Task 8.
Enter data into database (on paper sheets and/or on PDA)	Recording sheets/PDA or smart phone	After every survey	In some cases communities appear to find it easier to use pre-designed paper forms to record tree data in the field, although direct entry of data into the PDA is certainly possible and reduces chance of transcribing error.
Submit data to the National Forest Monitoring System	PDA, smart phone, or work station with internet connection	After every survey	If the National Forest Monitoring System is set up to receive data directly from the communities through a web-interface, transfer of data can be automated to reduce effort and error. A submission of data may trigger a set of responses, such as verification by a local FD office, generation of a report, or allocation of benefits.

Box 3.4.2 Limitations of data collection at the community level

As noted in the introduction, there are good reasons to include communities in the collection of data for REDD+. Such involvement supports ownership and commitment; together with (legal) recognition and receiving a just share of the benefits, communities are then strengthened as sustainable managers and custodians of the forest. Community involvement is the most cost-efficient mechanism to collect large volumes of basic data on the ground. (McCall 2011; Knowles et al 2010).

There are limitations however to the types of data that communities can reliably collect. The data are best limited to a set of basic forest properties, (though these data alone are not sufficient to compute above-ground biomass (see 3.4.3)

- Social/ geographical information – community and forest boundaries and claims, conflict areas, forest management types. Initial stage and periodic updating, say every five years.
- Type of forest, species identification, with common names (which should also be translated to scientific nomenclature). Initial and Periodic.
- Tree count. Annual.
- dbh measurement. Annual.
-

Measurements by community members are not always of consistently high quality over time, between stands, or between observers. Aside from occasional external verifications, data quality assessment in a given community can be augmented by jointly analyzing the data from many communities in a single ecological zone or forest type or forest management type.

If a community is producing data divergent from those of other communities, then the causes need investigation. They may be due to (see: Chave et al. 2004):

- errors in the tree measurement procedures;
- sampling uncertainty related to the size of the study plot;
- representativeness of the network of plots in the forest landscape, related to the stratification of the forest (e.g. forest belongs to another ecological zone);
- effectiveness of intervention (improved forest management) is different.

If the equipment (PDAs equipped with mobile GIS software, Smartphones, Tablets, GPS, measuring tapes, tree tapes, callipers, clinometers, etc.) is allocated as the property of the intermediaries, it can be used efficiently by many community forest groups in an area. An intermediary with three or PDAs / Tablets could service 12 or more communities per year (for cost estimates see Section 3.4.5). Appropriate methodology has been developed by several organisations and agencies, notably the K:TGAL project (see Box 3.4.3).

Communities need to be assisted in establishing the sampling plots. Marking the centre of the permanent plots with paint or plates on tree trunks, increases the reliability of the survey and reduces the standard error by ensuring that the same areas are measured each year. This can introduce bias, in that it identifies precisely where the measurements are being made, which could lead forest users to better protect those areas against degradation, e.g. by limiting the collection of firewood or poles or cattle grazing in those places. However this problem is not unique to community surveying, it would be the same with external surveyors. Locating the plots with a GPS is an alternative, but in densely forested areas the signal may be weak, giving a coarse determination of position.

Box 3.4.3 The *Kyoto: Think Global, Act Local* collaborative research project

The *Kyoto: Think Global, Act Local* (K:TGAL) research project was a joint endeavour of research institutes and NGOs in seven countries in Asia and Africa, led by the University of Twente with the support of ITC, in The Netherlands, from 2003 to 2009.

The K:TGAL project has prepared manuals intended for the training of intermediary staff in participatory forest inventory. It uses standard tree measuring equipment and PDAs for recording the data. It is assumed most staff would have had at least some intermediate (middle school) education, and that they are familiar with digital, but it is not a requirement that they have much forestry experience. The manuals can be downloaded from the K:TGAL website (www.communitycarbonforestry.org, under Resources and Publications, Community measuring monitoring and mapping) together with other supporting information. An updated version for use with Smartphones can be accessed at https://redd.ciga.unam.mx (under Publications, manuals)

Box 3.4.4 Manuals for guiding community forest monitoring

MacDicken, K.G. (1997) A Guide to Monitoring Carbon Storage in Forestry And Agroforestry Projects. Winrock International. http://www.winrock.org/ecosystems/files/carbon.pdf

Theron, L.-J. (2009) Carbon Stock Quantification. Training and Field Manual. Stellenbosch: Peace Parks Foundation, Climate Change Programme www.peaceparks.org

Verplanke, J.J. and E. Zahabu (2009) A Field Guide for Assessing and Monitoring Reduced Forest Degradation and Carbon Sequestration by Local Communities. www.communitycarbonforestry.org

Bhishma, P.S. et al. (2010) Forest Carbon Stock Measurement Guidelines for Measuring Carbon Stocks in Community-Managed Forests. Asia Network for Sustainable Agriculture and Bioresources (ANSAB), Kathmandu, Nepal. www.forestrynepal.org/publications/book/4772

Honorio Coronado, Eurídice N.; and Baker, Timothy R. (2010) Manual para el Monitoreo del Ciclo del Carbono en Bosques Amazónicos. Lima: Instituto de Investigaciones de la Amazonia Peruana / Universidad de Leeds. (54 p.) http://www.rainfor.org/upload/ManualsSpanish/Honorio_Baker2010%20Manual%20carbono.pdf

Peters-Guarin, G. and McCall, M.K. (2010) Community Carbon Forestry (CCF) for REDD. Using CyberTracker for Mapping and Visualising of Community Forest Management in the Context of REDD. KT-GAL.

Walker et al. (2011) A Field Guide for Forest Biomass and Carbon Estimation. Woods Hole Research Center, Woods Hole, MA, USA. www.whrc.org/resources/fieldguides/index.html

Hairiah, K. Dewi, S., Agus, F., Velarde, S., Ekadinata, A., Rahayu S., and van Noordwijk, M. (2011) Manual: Measuring Carbon Stocks Across Land Use Systems. World Agroforestry Centre http://www.worldagroforestry.org/sea/Publications/files/manual/MN0050-11/MN0050-11-1.PDF

Edwards, Karen; Henry Scheyvens; Jim Stephenson; and Taiji Fujisaki (2014) Community-Based Forest Biomass Monitoring. Training of Trainers Manual. Hayama, Kanagawa: Institute for Global Environmental Strategies (IGES) (216p.) http://pub.iges.or.jp/modules/envirolib/view.php?docid=4999.

SNV Vietnam and German Federal Ministry for Environment, Nature Conservation and Nuclear Safety http://www.snvworld.org/en/redd/publications/participatory-carbon-monitoring-manual-for-local-people.

CIGA-UNAM (2014) Manual for Community Technicians, Version 5. http://redd.unam.mx (Go to: Publications, Manuals)

3.4.3 Additional data requirements for biomass carbon

The communities may be in a good position to collect basic data from the forest, such as tree species, tree count and dbh, but these alone are not sufficient to compute above-ground biomass. It is necessary to have a parallel process to complement the basic data and be able to ascertain the quality of the locally-collected data.

The additional data required depend on the local conditions and prior information. For instance, locally relevant allometric equations are needed to calculate above-ground biomass and these equations require input parameters like tree height, tree branch height, or wood density. Such parameters can be collected using traditional forest inventory techniques, such as those described in sections 2.3 and 3.3. Even if no additional parameters are required beyond dbh, it is important to have a parallel process to sample measure dbh and tree counts with high accuracy, in order to validate the data input from communities. Standard statistical techniques can then be applied to establish whether the data received from communities are reliable.

3.4.4 Reliability and accuracy

Although some express doubts whether communities will be able to provide reliable, good quality data, the evidence is that they can. In the K:TGAL project, independent professional forest companies carried out surveys in three of the project sites in order to test the reliability of the communities' estimates of carbon stock. In every case, there was no more than 5% difference in the estimate of mean carbon stocks between the professionals and the community.

It is recommended that communities make annual measurements, even though official reporting periods in REDD+ may be longer than this. There are a number of reasons:

- This would maintain community involvement and sustain interest, and would provide a continuity of practice in the monitoring tools and procedures,
- It is an important mechanism to assess the quality of the data collection process - errors of measurement in a particular year may be more easily detected and eliminated. Annual measurement provides a robust approach to inventory.
- It can provide more timely insights into the effectiveness of REDD+ interventions.
- If forests are measured annually, communities will be more aware of changes in the forest.
- Annual fluctuations due to weather changes are common, over a longer trajectory those would to some extent be smoothed out.
- It is feasible that national REDD+ programs will have to offer annual incentives for participation in monitoring activities, rather than carbon payments at the end of a multi-year reporting period, - communities are unlikely to accept long waiting periods for payments.

The confidence level used in determining the number of sample plots is a major factor in the cost of carrying out forest surveys. A confidence level of 95% rather than 90% requires many more sample plots (i.e. more work by communities in making measurements). On the other hand, less uncertainty in the assessment of above-ground biomass will most likely lead to more confident estimates of emission reduction or removals and thus higher payments or other benefits; see Section 2.5 for more details.

The number of sampling plots required to achieve a given confidence level and maximum error is calculated following a pilot sampling survey. The statistical methods for this are clearly explained in the manuals and in the IPCC Good Practice Guide. A protocol regarding the level of confidence required is one of many parameters that need to be determined at national level, for standard application in all community monitoring within a country's REDD+ programme.

3.4.5 Costs and payments

The K:TGAL project estimated costs of community forest inventory as ranging between $1 and $4 per hectare per year (2005-2009 period), including day wages for the community members involved and the intermediary, and a factor for 'rental' of the equipment (PDA, GPS, etc.). The costs in the first year are higher than this, given the substantial inputs by the intermediary in training community members and establishment of the sampling plots. Average costs are much lower in large, homogeneous forests owing to economies of scale. The equivalent costs if professional organizations were to be employed instead of communities are two to three times higher than this. (Skutsch et al. 2011; also see: Knowles et al. 2010)

Emission reductions and enhanced removals may be credited over longer time intervals (e.g. 5 years), but local communities will need to be paid annually or even more frequently to maintain their commitment to the process. How payments are made, and on what basis, are questions which the government REDD+ agency must decide.

Essentially there are three options:
A. Communities implement REDD+ activities to reduce deforestation and forest degradation, and as a condition of their participation, they are required to survey the forest regularly to assess the amount of biomass. Benefits are made over to them based on the amount of emission reductions or enhancement removals they achieve. In this option, monitoring is an implantation or transaction cost which has to be carried by the community itself. The national REDD+ agency is likely to be strongly insistent on external verification with this option, because, in effect, the communities themselves are providing the data from which their carbon payments will be determined.
B. Communities engaging in REDD+ activities are required to make regular surveys but they are paid for this activity, independently from any benefits they may receive for carbon performance. In this option, there is no link with emission reductions or enhanced removals – payment is made for the survey services rendered.
C. Surveys at community level are managed by the staff of a government REDD+ agency, or say, an NGO, which may hire local community labour to carry out this work.

3.4.6 Options for external, independent assessment of locally-collected biomass data

National governments will need an independent mechanism to verify the data monitored by local communities, particularly if benefit distribution is based on these data. One of the options is statistical analysis, as briefly explained above, but at larger scales remote sensing is an obvious choice; see Sections 2.2 and 2.3. In order to enable independent assessments, forest specialists should make complete inventories at the time of establishing the sampling protocol for community REDD+ projects. A proper stratification of the forest, with due consideration for those properties of the forest that are easily detected on satellite imagery, will be of prime importance, as will the detailed description of the forest structure.

The data that are being collected by the communities can be correlated to satellite imagery using a number of techniques.
The first one looks at the (assumed) homogeneity of the strata in the forest, while the second one establishes the correlation between biomass as measured in the forest and reflectance recorded in the satellite image:

- Assuming that the stratification of the forest has led to homogenous units, the reflectance characteristics of the pixels in the stratum should also be similar at the time the stratification is made (i.e. it has a uniform look in the imagery). At a later stage, when some management intervention has been implemented and the communities are collecting data, a new image can be analysed for its uniformity. If the uniformity is no longer present, or weaker than before, it may be that part of the forest was deforested or some communities are not managing the forest as they should. Note that the reflectance itself may have changed if the biomass has changed, either through continued but reduced degradation or because of forest enhancement. Homogeneity, and thus uniformity in the satellite image, may also increase if the forest is more uniformly degraded or enhanced; this may be avoided by applying a more strict stratification initially.
- Using a standard image analysis technique, the biomass assessment made by the communities can be correlated to the reflectance in the satellite image. In open woodlands and forest types that have a distinct seasonal dynamic (e.g. leaf shedding in the dry season) the assessment (and its timing) has to be compatible with the measurements made by the local community. Outliers in the correlation indicate some issue with the data collection process (or deficient stratification). When widely implemented, the sheer volume of locally-collected data, probably even when a detailed stratification of the forest is made, makes it possible to use only a (random) sample of the local data.

3.4.7 Community Monitoring of Safeguards in REDD+

As the goals and politics of REDD+ have developed, more non-carbon measures and indicators are being drawn in, notably the concepts of safeguards. (Though even before that, the objective of ‘sustainable management of forests was already included in MRV discourse). REDD+ policies and directives call for additional environmental and social-economic information on CFM. Some are directly connected to the biomass surveys which form the core of this chapter, and some are more akin to social and institutional surveys. Much of this information can be provided by measurements and monitoring by community members.

The full gamut of safeguards runs from: environmental and biodiversity, to objectives of policy compatibility, good governance, human rights and social equity, and calls for stakeholder participation and respect for the rights (and the knowledge) of indigenous peoples and local communities. See Table 3.4.3; Chhatre et al. 2012)

Table 3.4.3 Safeguarding Environmental and Social issues in REDD+.

SAFEGUARDS (Stated in Decisions 1/CP.16, appendices)	**COMMUNITY SURVEY TOOLS & METHODS**
i. ***Policy objectives:*** consistency with national forest programmes and international conventions and agreements,	Policy impact surveys deployed by communities – Indicators in specific forest management zones
ii. Governance: effective and transparent forest governance structures	Surveys of awareness of, and participation in, governance
iii. Human rights objectives: participation especially indigenous peoples and forest local communities. Use of local specialised knowledge	Surveys of participation in forest management activities, and, in decision-making. Tracking use of local/ indigenous forest & management knowledge
iv. Socio-economic objectives: social benefits, related to benefit-sharing.	Social surveys, expenditure surveys, etc. for categories of forest users
v. ***Biodiversity objectives:*** conservation of natural forest,	Field observations, camera traps, sound recordings, species identification, etc. by

	community members during forest activities.
vi. Environmental objectives: environmental benefits, risks reversals of REDD+ and emissions displacement – change of land use/land cover, leakage	Observations, volunteered information, recording protocols

adapted from Muchemi et al. (2014)

Under REDD+, countries will develop indicators for safeguards, and they will be required to report on how safeguards are being addressed and respected. Monitoring for safeguards is an activity which can be carried out by communities alongside their forest measurements. This would require the development of protocols and survey methods which the communities could self-apply. There is considerable evidence that communities are able to make simple biodiversity measurements, based on key species (Danielsen et al. 2009; 2011). If communities survey annually their forest and also make safeguard assessments, this information can feed back to national governments and enable fine-tuning of policy choices.

3.4.8 Mobile IT for community surveys

Technological potential lies in the ubiquity of mobile IT devices and apps which have greatly increased functionalities, at lower cost, and are increasingly easy to handle.

Hardware: Rugged Tablets and Smartphones with large memory for storing the necessary imagery or maps and software, with GPS capability of sufficient precision, camera and video, and with internet connectivity for downloading images and uploading data are replacing the PDA set-ups. The prime advantages are ease of use, convenience of supply and repair, and especially to benefit from the familiarity of ordinary people with mobile phones – very easy for young community members to ‘upgrade’ to a Smartphone. Currently, costs of Smartphones are high – but dropping fast, and not prohibitive. A common business plan is that the local intermediaries or brokers would be the resource holders of Smartphones in the near future, until unit prices drop further.

Imagery: Geo-referenced images as bases for mapping community forest boundaries and strata, and plots, etc., are easily available at very low cost or free, from Google Earth or Virtual Earth or other virtual globes (Peters-Guarin and McCall 2011). The cost of LIDAR which could provide very high precision imagery is also dropping.
There is big potential in the use of UAVs / drones for communities (or intermediaries) to acquire their own dedicated imagery from a range of air-borne sensors, and have their own capacity for real-time monitoring of forest threats, fires, invasions, etc. There are obvious challenges of current costs, skills and maintenance, and of privacy, safety and security, but the trend is already apparent (Paneque-Gálvez et al. 2014).

Apps: Apps with very user-friendly interface between users and the devices (PDAs, Tablets, Smartphones) are being adapted for forest and tree measurement with simplified data recording and clear sequential instructions. In 2014 these are CyberTracker (South Africa, Mexico) and Sapelli (UK), both with special attention to non-literate users by using icons, Plataforma eREDD (Mexico), Google’s ODK (Open Data Kit) and GeoODK, and Poimapper (Finland). Most of them, e.g. CT, Sapelli, and ODK, work well offline without network connectivity.

Table 3.4.4 (Potential) Mobile IT Platforms and Survey Tools.

Tool	Description, Features	License Type	IT Skills Required	Egs of Users	OS Mobile devices Data storage
CyberTracker	Software originally	Freeware	Computer	CIGA-REDD	CT desktop,

http://cybertracker.org/	for game tracking. Has developed into global monitoring tool, 1000's users. User-friendly icon-driven interface for mobile devices.	Open Source	skills & basic knowledge databases – for initial design – not for operating	UNAM, Mexico 'Manual for Community Technicians'http://redd.ciga.unam.mx/files/CommunityManual.pdf	Windows, Apple MacOSX; Android Smartphones, Samsung Galaxy Camera, Tablets Windows Mobile PDA. Private database, desktop
Google OpenDataKit http://opendatakit.org/	Set of tools designed to facilitate mobile data collection. Data collection forms Collect data on Mobile device Aggregate data on server	Freeware Open Source	Computer skills & basic knowledge databases – for initial design.	Global Canopy Programme, Guyana, Brazil	Android. Private database, desktop, or Cloud
GeoODK www.geoodk.com	Developed from ODK. 'Formhub' for database management. GeoTrace (walk around area)	Freeware Open Source	Online and offline mapping components	University of Maryland / IIASA. Not yet community carbon monitoring	Android. Private database, desktop, or Cloud
Plataforma eREDD+	Local NRM activities. Online/offline mobile and historic data collection, data storage, analysis and visualisation. Normalised databases for: biomass, RIL-C, water quality, &biodiversity.	Testing phase. Freeware	Basic computer skills	Alianza Mexico REDD+;Fortalecimiento REDD+; Coperación Sur Sur; Proyecto LAIF	WEB Platform: SQL Server/Windows. NET/IIS Android devices. Data Analysis Tool: DAR OLAP Geographic Analysis Tool: Geo Server
Sapelli http://www.ucl.ac.uk/excites/software/sapelli	Mobile data collection and sharing platform. Sapelli Collector pictorial decision trees icon-driven interfaces. Sapelli Data Sender forward SMS messages Sapelli Maps	Sapelli Launcher replaces Android UI with text-free app. launcher interface.		UCL Extreme Citizen Science (ExCiteS) Central Africa	Cloud storage – Amazon Server & Dropbox
Poimapper http://poimapper.com/	Allows mobile users to collect, share, and visualize geographically tagged data in real-time.	Copyright. Free version for single user. Price; reductions for NGOs	Support from developing team needed.	Mostly in Health applications. No users identified in community forest mngt.	Android Cloud or private database storage.

Sources: Adapted from: Larrazabal et al. (2012); WWF/USGS/GCP (2014); websites

3.4.9 Conclusions – Drivers and principles of community monitoring

Local Community Interests in Community-based forest monitoring – *'What's in it for the community?'*

Although the immediate external driver for community monitoring in this context is the support of local REDD+ activities, there are a range of reasons why communities may be disposed to be involved in such surveys. Local studies and literature identify many specific reasons why communities are already involved in monitoring their local forest conditions and changes, or have a serious potential interest in doing so.

The community may already be involved in other PES programmes or future opportunities – e.g. PES for hydrological services, erosion control, biodiversity services, endangered species, pollenisation, landscape aesthetics, etc. Surveying and monitoring change in forest resources can be linked with a more comprehensive approach to environmental service provision, for compensation from off-site beneficiaries. Management of forest and of territory in general by local communities is undertaken in a holistic manner; it is not a disarticulated management of individual resources or service provision. Thus, when communities choose to take up the programmes and procedures of forest monitoring, they can relatively easily transfer the monitoring procedures and skills to a 'community portfolio' of environmental services. The data conventions, frequency and scale of monitoring are of course specific to the environmental service claimed (carbon, biodiversity, hydrological provision); but the experience developed in forest monitoring for carbon can be transferred to other environmental services.

Similarly, many communities are involved in FSC or other Certification of forest products and forest landscapes, and, whether certified or not, many communities are engaged with specific forest products which are already economically valuable to the community, e.g. NTFPs, honey, medicinal plants, bamboo production. Along the same lines, rural communities are increasingly looking towards eco-tourism opportunities, and thus need to monitor and advertise the positive status of the landscape.

Frequently the most significant driver at the local level is political-cultural – the monitoring of the community territory and its forest areas in connection with, and complementary to, claims for customary territorial rights and the community's entitlement to lands and land resources. And equally, for making claims for lands which have been alienated or are being invaded. A deep-rooted component of this, especially for indigenous peoples, is the protection and conservation of sacred places and sacred landscapes, natural or constructed.

Mixed interests – both internal and external

Another driver, which relates to both internal and external interests, is to monitor the stresses affecting local forest management or NRM in general – deforestation and degradation locations and causes, damage to NTFPs, natural hazards - notably forest fires, pollution sources, forest pests and diseases, or in other resources, etc. This information on the outcomes and drivers of deforestation and degradation is vital for evaluating national public policies and programmes.

For effective environmental planning the government needs data on the nature of drivers at local level and on the effectiveness of measures that are undertaken. Communities can supply data on these alongside their other measurements in the forest, thus assisting national REDD+ agencies in their assessments of policy effectiveness under different conditions. Although many countries appear to be opting for PES-type incentives under REDD+, the details of how these are implemented make a considerable difference to their effectiveness. Depending on the types of forest (humid tropical, dry tropical, temperate), the specific threats of deforestation, and the population pressure, different policies and incentive plans are necessary. Some policies may be more effective in targeting degradation and forest enhancement, while others may focus on deforestation.

Community monitoring might also provide a basis for whatever REDD+ benefit distribution system is selected by countries. In principle, communities could be awarded benefits for any decreases they achieve in rates of deforestation and degradation, and any increases in stocks. In practice, this may be very difficult to achieve (Balderas Torres and Skutsch, 2012), since it is unlikely that deforestation/ degradation baselines will be created for each and every community participating within a national REDD+ programme. However, forest enhancements can easily be measured by communities directly meaning that that in principle they could be rewarded for any enhancement of stock (sequestration) they achieve, based on the monitoring surveys carried out.

Links to national MRV
It is also suggested that community-monitored data could be integrated with national level forest data systems, providing more detailed ´densified´ data for areas where communities are active in managing and monitoring forests, gradually raising the reliability of overall national MRV systems (Pratihast et al 2011, 2013; Skutsch et al 2014). Moreover community assessments of forest cover type may provide important inputs to remotely sensed data on forest cover change (Vergara-Asenjo et al 2014).

FPIC – free, prior, informed consent.

Community forest monitoring is, by definition, a community participatory activity, and therefore is subject to the same political, ethical, and moral principles as any interactive process between powerful external forces and less powerful peripheral local peoples. In any case, FPIC ('free, prior, and informed consent') is a specified requirement of any REDD+ project or activity, as demanded by UN-REDD (ONU-REDD 2013; UN-REDD 2011, 2012). This is as valid for the processes of community involvement in surveying and monitoring as it is for any part of a REDD+ community project. FPIC requirements are highly demanding, very complicated and time-consuming to implement; rarely are they fully adhered to. Nevertheless, they must be recognised and operationalised as far as possible.

'Free' refers to the process (of agreement to participate in monitoring) being self-directed by the community from whom consent is being sought, unencumbered by coercion, expectations or timelines externally imposed. 'Prior' implies that time is provided to access and understand the information on the monitoring activities. Information must be provided before activities are initiated, and for instance, decision-making timelines of local/ indigenous peoples must be respected. 'Informed' refers to the information that should be provided prior to seeking consent and during the consent process. Information about the community monitoring activities and outputs should be accessible, clear, accurate, transparent, in appropriate language, covering positive and negative aspects, and any consequences if the people withhold their consent. It should reach even remote communities, women and the marginalized, and be on-going.

'Consent' refers to decisions being made by local communities reached through customary decision-making processes. The collective right to give or withhold consent applies to "all projects, activities, legislative and administrative measures and policies that directly impact the lands, territories, resources, and livelihoods of indigenous peoples and other local communities", and thus includes monitoring activities.
A significant aspect of 'consent' is the question of 'ownership' of the products of the participatory monitoring – the survey results, forest and carbon measurements, maps and any other data.

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4 COUNTRY CAPACITY BUILDING

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4.1 SCOPE OF SECTION

Countries undertake national forest monitoring for a number of reasons - economic, socio-cultural and environmental. In most developing countries the quality of current forest monitoring is considered not satisfactory for an accounting system of carbon credits (Holmgren et al. 2007). The development of forest monitoring systems for REDD+ is a fundamental requirement and area of investment for participation in the REDD+ process. Despite the broader benefits of monitoring national forest resources per se, there is a set of specific requirements for establishing a national forest carbon monitoring system for REDD+ implementation. They include:

- ☐ The considerations of a national REDD+ implementation strategy.
- ☐ Systematic and repeated measurements of all relevant forest-related carbon stock changes. Robust and cost-effective methodologies for such purpose exist (UNFCCC, 2008a).
- ☐ The estimation and reporting of carbon emissions and removals on the national level using the IPCC Good Practice Guidance on Land Use Land Use Change and Forestry given the related requirements for transparency, consistency, comparability, completeness, and accuracy.
- ☐ The encouragement for the monitoring systems and results to review independently.

The design and implementation of a monitoring system for REDD+ can be understood as investment in information that is essential for a successful implementation of REDD. This section provides a more detailed description of required steps and capacities building upon the GOFC-GOLD sourcebook recommendations.

4.2 BUILDING NATIONAL CARBON MONITORING SYSTEMS FOR REDD: ELEMENTS AND CAPACITIES

4.2.1 Key elements and required capacities - overview

The development of a national monitoring system for REDD+ is a process. A summary of key components and required capacities for estimating and reporting emissions and removals from forests is provided in Table 4.2.1. The first section of planning and design should specify the monitoring objectives and implementation framework based on the understanding of:

- ☐ The status of international UNFCCC decisions and related guidance for monitoring and implementation.
- ☐ The national REDD+ implementation strategy and objectives.

- Knowledge in the application of IPCC LULUCF GPG.
- Existing national forest monitoring capabilities.
- Expertise in estimating terrestrial carbon dynamics and related human-induced changes.
- The consideration of different requirements for monitoring forest changes in the past (historical data) and for the future (accounting period).

The planning and design phase should result in a national REDD+ monitoring framework (incl. definitions, monitoring variables, institutional setting etc.), and a plan for capacity development and long-term improvement and the estimation of anticipated costs.

Implementing measurement and monitoring procedures to obtain basic information to estimate GHG emissions and removals requires capabilities for data collection for a number of variables. Carbon data derived from national forest inventories and permanent plot measurements, and remote sensing-based monitoring (primarily to estimate activity data) are most commonly used. In addition, information from the compilations of forest management plans, independent reports, and case studies and/or models have provided useful forest data for national monitoring purposes. Irrespective of the choice of method, the uncertainty of all results and estimates need to be quantified and reduced as far as practicable. A key step to reduce uncertainties is the application of best efforts using suitable data source, appropriate data acquisition and processing techniques, and consistent and transparent data interpretation and analysis. Expertise is needed for the application of statistical methods to quantify, report, and analyze uncertainties, the understanding and handling of error sources, and approaches for a continuous improvement of the monitoring system both in terms of increasing certainty for estimates (i.e. move from Tier 2 to Tier 3) or for a more complete estimation (include additional carbon pools).

All relevant data and information should be stored, updated, and made available through a common data infrastructure, i.e. as part of national GHG information system. The information system should provide the basis for the transparent estimation of emissions and removals of greenhouse gases. It should also help in analysis of the data (i.e. determining the drivers and factors of forest change), support for national and international reporting using a common format of IPCC GPG reporting tables, and in the implementation of quality assurance and quality control procedures, perhaps followed by an expert peer review.

Table 4.2.1. Components and required capacities for establishing a national monitoring system for estimating emissions and removals from forests.

Phase	Component	Capacities required
Planning & design	1. Need for establishing a forest monitoring system as part of a national REDD+ implementation activity	• Knowledge on international UNFCCC decisions and SBSTA guidance for monitoring and implementation • Knowledge of national REDD+ implementation strategy and objectives
	2. Assessment of existing national forest monitoring framework and capacities, and identification of gaps in the existing data sources	• Understanding of IPCC LULUCF estimation and reporting requirements • Synthesis of previous national and international reporting (i.e. UNFCCC national communications & FAO Forest Resources Assessment) • Expertise in estimating terrestrial carbon dynamics, related human-induced changes and monitoring approaches • Expertise to assess usefulness and reliability of existing capacities, data sources and information
	3. Design of forest monitoring system driven by UNFCCC reporting requirements with objectives for historical data and future monitoring	• Detailed knowledge in application of IPCC LULUCF good practice guidance • Agreement on definitions, reference units, and monitoring variables and framework • Institutional framework specifying roles and responsibilities • Capacity development and long-term improvement planning • Cost estimation for establishing and strengthening institutional framework, capacity development and actual operations and budget planning

Continued…

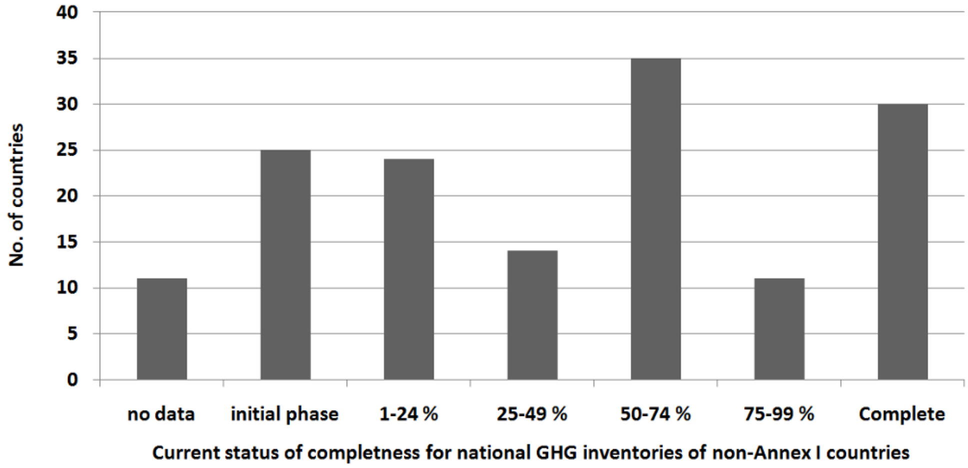
Phase	Component	Capacities required
Monitoring	4. Forest area change assessment (activity data)	• Review, consolidate and integrate the existing data and information • Understanding of deforestation drivers and factors • If historical data record insufficient – use of remote sensing: o Expertise and human resources in accessing, processing, and interpretation of multi-date remote sensing imagery for forest changes o Technical resources (Hard/Software, Internet, image database) o Approaches for dealing with technical challenges (i.e. cloud cover, missing data)
	5. Changes in carbon stocks	• Understanding of processes influencing terrestrial carbon stocks • Consolidation and integration of existing observations and information, i.e. national forest inventory or permanent sample plots: o National coverage and carbon density stratification o Conversion to carbon stocks and change estimates • Technical expertise and resources to monitor carbon stock changes: o In-situ data collection of all the required parameters and data processing o Human resources and equipment to carry out field work (vehicles, maps of appropriate scale, GPS, measurements units) o National inventory/permanent sampling (sample design, plot configuration) o Detailed inventory in areas of forest change or "REDD+ action" o Use of remote sensing (stratification, biomass estimation) • Estimation at sufficient IPCC Tier level for: o Estimation of carbon stock changes due to land use change o Estimation of changes in forest areas remaining forests o Consideration of impact on five different carbon pools
	6. Emissions from biomass burning	• Understanding of national fire regime and fire ecology, and related emission for different greenhouse gases • Understanding of slash and burn cultivation practice and knowledge of the areas where being practiced • Fire monitoring capabilities to estimate fire effected area and emission factors: o Use of satellite data and products for active fire and burned area o Continuous in-situ measurements (particular emission factors)
	7. Accuracy assessment and verification	• Understanding of error sources and uncertainties in the assessment process • Knowledge on the application of best efforts using appropriate design, accurate data collection, processing techniques, and consistent and transparent data interpretation and analysis • Expertise on the application of statistical methods to quantify, report and analyze uncertainties for all relevant information (i.e. area change, change in carbon stocks etc.) using, ideally, a sample of higher quality information
Analysis & reporting	8. National GHG information system	• Knowledge on techniques to gather, store, and analyze forest and other data, with emphasis on carbon emissions from LULUCF • Data infrastructure, information technology (suitable hard/software) and human resources to maintain and exchange data and quality control
	9. Analysis of drivers and factors of forest change	• Understanding and availability of data for spatio-temporal processes affecting forest change, socio-economic drivers, spatial factors, forest management and land use practices, and spatial planning • Expertise in spatial and temporal analysis and use of modelling tools
	10. Establishment of reference emission level and regular updating	• Data and knowledge on deforestation and forest degradation processes, associated GHG emissions, drivers and expected future developments • Expertise in spatial and temporal analysis and modelling tools • Specifications for a national REDD+ implementation framework
	11. National and international reporting	• Expertise in accounting and reporting procedures for LULUCF using the IPCC GPG • Consideration of uncertainties and understanding procedures for independent international review

4.2.2 Key elements and required capacities - GHG inventories

The discussion of requirements and elements (see Table 4.2.1) emphasizes that comprehensive capacities are required for the monitoring, reporting and accounting of emissions and removals of GHG from forest land. The development of UNFCCC national communications has stimulated support and engagement for countries to establish national GHG inventories and related national monitoring and reporting capacities. Figure 4.2.1 highlights the current status and the range of completeness for national GHG inventories. About 1/5 of non-Annex I Parties are listed with a fully developed inventory.

An additional 46 countries have taken significant steps with inventories in the range of 50-100 % complete. About half of the countries currently have systems less than 50% complete. Although the information in Figure 4.2.1 refers to the establishment of full GHG inventories, where the LULUCF sector is only one component, Figure 3.5.1 provides a sense of a current capacity gap for national-level GHG estimating and reporting procedures using the IPCC GPG.

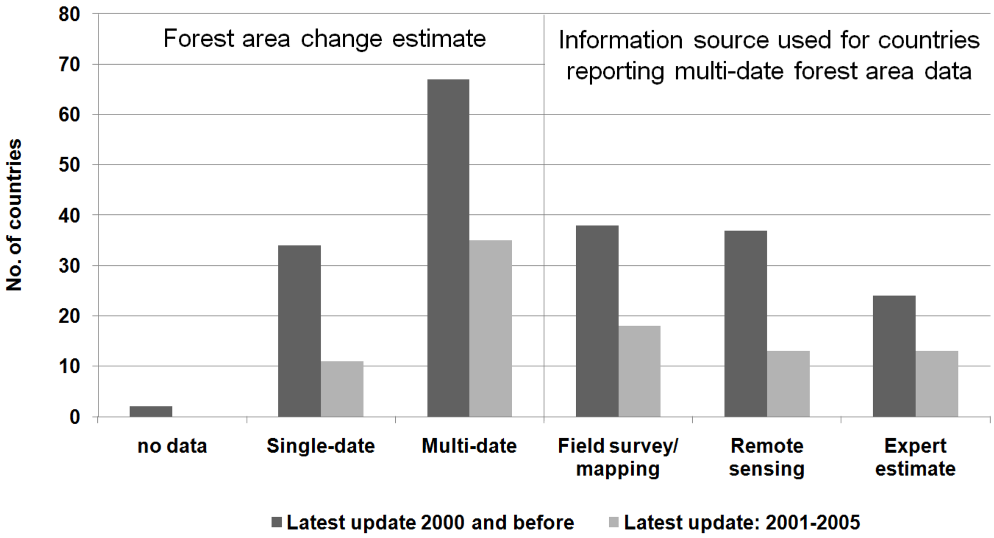
Figure 4.2.1. Status for completing national greenhouse gas inventories as part of Global Environment Facility support for the preparation of national communications of 150 non-Annex I Parties (UNFCCC, 2008b).



A status of country capacities for the monitoring of forest area change and changes in forest carbon stocks may be inferred from analyzing the most recent FAO global Forest Resources Assessment (FRA) for 2005 (FAO 2006). Assuming that all available and relevant information have been used by countries to report under the FRA, Figures 4.2.2 and 4.2.3 summarize the relevant capacities for non-Annex I Parties.

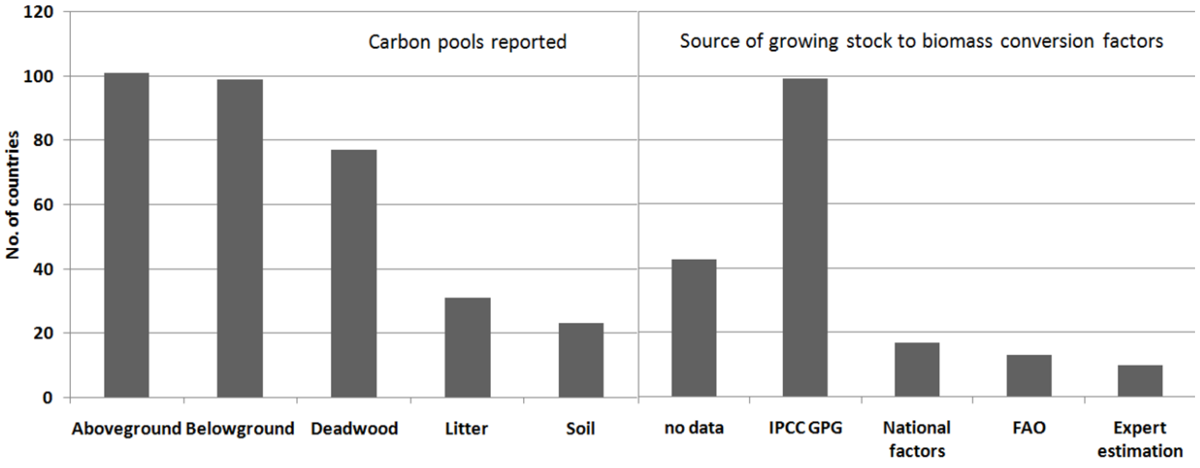
In terms of monitoring changes in forest area, Figures 4.2.2 highlights that almost all non-Annex I Parties were able to provide estimate forest area and changes. About two-thirds of countries provided this information based on multi-date data; about one-third reported based on single-date data. Most of the countries used data from the year 2000 or before as most recent data point for forest area, while 46 of 149 countries we able to supply more recent estimates. Of the countries that used multi-date information there is an almost even distribution for the use of information sources between field surveying and mapping, remote sensing-based approaches, and, with less frequency, for expert estimates (Note: countries may have used multiple sources).

Figures 4.2.2. Summary of data and information sources used by 150 non-Annex I Parties to report on forest area change for the FAO FRA 2005 (FAO 2006).



A smaller number of countries provided estimates for carbon stocks (Figure 4.2.3). 101 of 150 countries reported on the overall stocks in aboveground carbon pool. Since the aboveground and belowground carbon pools are correlated almost the same number of countries reported on the carbon in below ground vegetation. Fewer countries were able to provide data on the other pools, in particular for carbon in the soils 23 (countries). The reported forest carbon pool estimates are primarily based on growing stock data as primary observation variable. Of the 150 non-Annex Parties, 41 reported no growing stock data. 75 countries provided single-date and 34 multi-date growing stock data. A number of different sources are applied by countries for converting growing stocks to biomass (and to carbon in the next step), with the IPCC GPG default factors being used most commonly (Figure 4.2.3). The use of these default factors would refer to a Tier 1 approach for estimating carbon stock change using the IPCC GPG. Only 17 countries converted growing stock to biomass using specific and, usually, national conversion factors.

Figure 4.2.3. Summary of data for five different carbon pools reported (left) and information sources used by 150 non-Annex I Parties to convert growing stocks to biomass (right) for the FAO FRA 2005 (FAO 2006, countries may have used multiple sources for the conversion process).



Figures 4.2.2 & 4.2.3 emphasize the varying level of capacities among non-Annex I Parties. Given the results of FAO's FRA 2005, the majority of countries have limitations in providing a complete and accurate estimation of GHG emissions and removals from forest land. Some gaps in the current monitoring capacities can be summarized by considering the five UNFCCC reporting principles:

- **Consistency**: Reporting by many countries is based either on single-date measurements or on integrating different heterogeneous data sources rather than using a systematic and consistent monitoring;
- **Transparency**: Expert opinions, independent assessments or model estimations are commonly used as information source for forest carbon data (Holmgren et al. 2007); often causing a lack of transparency in the methods used;
- **Comparability**: Few countries have experience in using the IPCC GPG as common estimation and reporting format among Parties;
- **Completeness**: The lack of suitable forest resource data in many non-Annex Parties is evident for both area change and changes of carbon stocks. Carbon stock data for aboveground and belowground carbon are often based on estimations or conversions using IPCC default data and very few countries are able to provide information on all five carbon pools.
- **Accuracy**: There is limited information on error sources and uncertainties of the estimates and reliability levels by countries and approaches to analyze, reduce, and deal with them for international reporting and for implementation of carbon crediting procedures.

In a 2009 study[114], information from various consistent global information sources was analyzed to assess current national monitoring capabilities of for 99 tropical non-Annex I Parties (Figure 4.2.4). The assessment of current monitoring capabilities has emphasized that the majority of countries have limitations in their ability to provide a complete and accurate estimation of greenhouse gas (GHG) fluxes and forest losses. Less than 20% of the countries have submitted a complete GHG inventory so far, and only 3 out of the 99 countries currently have capacities considered to be very good for both forest area change monitoring and for forest inventories. The current capacity gap can be defined as the difference between what is required and what currently exists for countries to measure and verify the success of REDD+ implementation actions using the IPCC GPG. As a synthesis of this study, the figure below indicates the current distribution where the largest capacity gaps exist for countries:

- that have limited experience in estimation and reporting of national GHG inventories, in application of the IPCC GPG, and with limited engagement in the UNFCCC REDD+ process so far;
- with low existing capabilities to continuously measure forest area changes and changes in forest carbon stocks as part of a national forest monitoring system; reporting carbon stock changes on the IPCC Tier 2 level is considered a minimum requirement;
- that face particular challenges for REDD+ implementation that may not be relevant for all countries, (e.g. they have high current deforestation rates and significant emissions from forest degradation, biomass burning and soil carbon stocks are currently not measured on a regular basis) and require investments to observe more IPCC key categories and move towards Tier 3 level measurements; and
- where the availability of useful data sources for REDD+ monitoring is constrained. In this study the focus is on the availability of common satellite data sources (i.e. Landsat, SPOT) that may be limited in their use due to lack of receiving stations,

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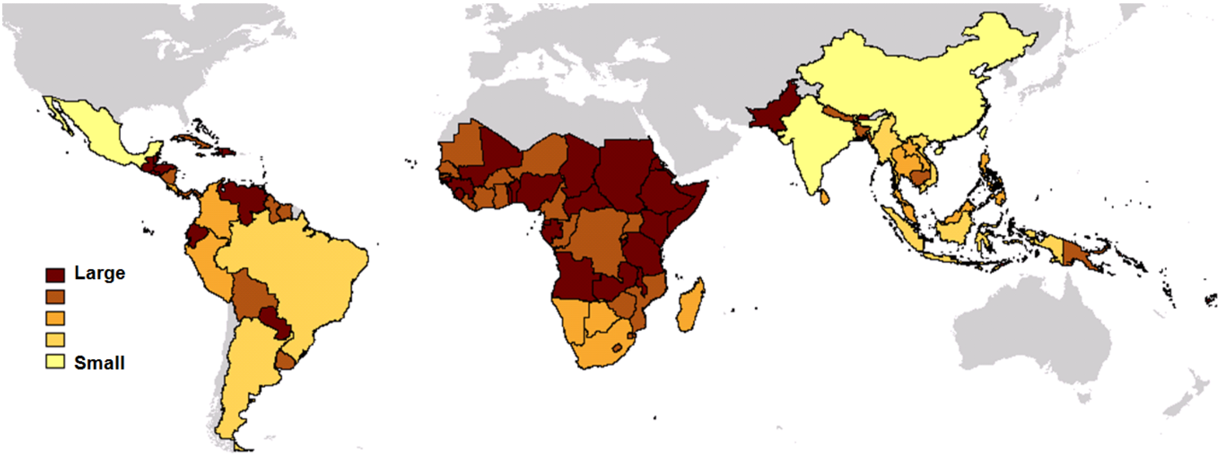
[114] available at http://princes.3cdn.net/8453c17981d0ae3cc8_q0m6vsqxd.pdf

persistent cloud cover, seasonality issues, topography or inadequate data access infrastructure.

Capacity building activities should consider the different entry points for countries in this process and work towards an ultimate goal that all interested countries have a minimum level of monitoring capacity in place within the next few years.

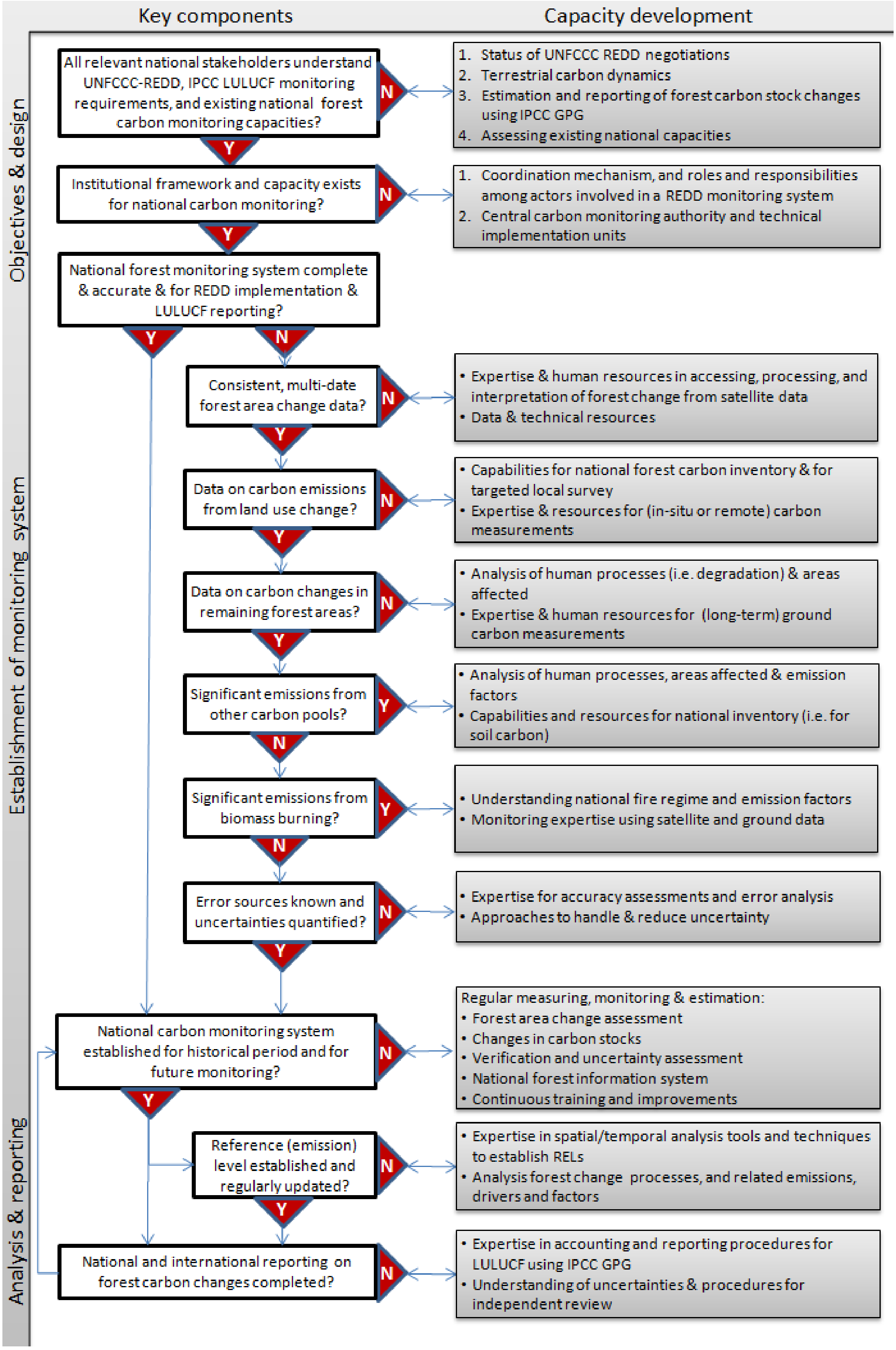
Figure 4.2.4. Spatial distribution of the capacity gap for the different countries analyzed.



4.2.3 Key elements and required capacities - current monitoring capacities

The pathways and cost implications for countries to establish REDD+ monitoring system requires understanding of the capacity gap between what is needed for such a system (see Table 4.2.1) and the status of current monitoring capacities. The important steps to be considered by countries are outlined in Figure 4.2.5. Fundamental to this is understanding of all relevant national actors about the international UNFCCC decisions and SBTSA guidance on REDD, the status of the national REDD+ implementation activities, knowledge of IPCC LULUCF good practice guidance and expertise in terrestrial carbon dynamics and related human-induced changes.

Figure 4.2.5. Flowchart for the process to establishing a national monitoring system linking key components and required capacities (see Table 4.2.1).



Uncertain input data (i.e. on forest area change and C stock change) is a common phenomenon among non-Annex I Parties but adequate methods exist to improve monitoring capacities. A starting point is to critically analyze existing forest data and monitoring capabilities for the purpose of systematic estimation and reporting using the IPCC LULUCF GPG. Table 4.2.2 lists several key existing data sources that are commonly considered useful.

Table 4.2.2. Examples of important existing data sources useful for establishing national REDD+ monitoring.

Variable	Focus	Existing records	Existing information
Area changes (activity data)	Deforestation	Archived satellite data & airphotos Field surveys and forest cover maps Maps of forest use and human infrastructures	Maps & rates of deforestation and /or forest regrowth Land use change maps National statistical data
	Forest regrowth		
Changes in carbon stocks / emission factors	Land use change (deforestation)	Forest inventory, site measurements Permanent sample plots, research sites Forest/ecosystem stratifications Forest concessions/harvest estimates Volume to carbon conversion factors Regional carbon stock data/maps	Carbon stock change and emission/ha estimates
	Changes in areas remaining forests		Long-term measurements of human induced carbon stock changes
	Different C-pools (i.e. soils)		
Biomass burning	Emissions of several GHG	Records of fire events (in-situ) Satellite data Emission factor measurements Records of areas under slash and burn cultivation	Burnt area map products Fire regime, area, frequency & emissions
Ancillary (spatial) data	Drivers & factors of forest changes	Topographic maps Field surveys Census data	GIS-datasets on population, roads, land use, planning, topography, settlements

The assessment of existing and required capacities should independently consider the different IPCC variables. In case there are no consistent times series of historical forest area change data, the country should consider using archived satellite data and establish the required monitoring capacities. Forest inventory data are currently the most common data source for the estimation of changes in forest carbon stocks. However most of the existing and traditional forest inventories have not been designed for carbon stock assessments and have limited use for this purpose. Ideally and in some contrast to traditional inventories, the design for national carbon stock inventory should consider the following requirements:

- **Stratification** of forest area: by carbon density classes and relevant human activities effecting forest carbon stocks;
- **Coverage**: full national coverage with most detail and accuracy required in areas of "REDD+ relevant activities";
- **Site measurements**: emphasize on measuring carbon stocks, potentially in all carbon pools;
- **Time**: consistent and recurring measurements of carbon stock change, i.e. for deforestation and in areas remaining as forests (i.e. degradation); and

- **Uncertainties**: verification and considerations for independent international review.

The investments and priority setting for monitoring carbon stock changes related to forests, in all carbon pools (i.e. soils, biomass burning) may depend on how significant the related human-induced changes are for the overall carbon budget and the national REDD+ implementation strategy are. For example, if the country has no fire regime and no significant emission from biomass burning it is not necessary to develop a related monitoring. The monitoring of carbon changes in forests remaining as forests (both increase and decrease) is generally less efficient than for the case deforestation, i.e. lower carbon stock changes per ha versus higher monitoring costs and, usually, lower accuracies. On the other hand, monitoring of forest degradation is important since the cumulative emission can be significant and updated data are required to avoid displacement of emissions from reduced deforestation. A country should have understanding and regularly monitor the human processes causing loss or increases in forest carbon stocks, i.e. through a recurring assessment of degraded forest area. However, the level of detail and accuracy for actual carbon stock changes should be higher for countries interested in claiming credits for their activities (i.e. reducing emissions from forest degradation). In this case, the establishing the REDD+ monitoring system should put particular emphasis in building the required capacities that usually require long-term, ground-based measurements. A similar procedure maybe suggested for the monitoring of changes in other carbon pools. To date, very few developing countries report data on soil carbon, even though emissions maybe significant, i.e. emissions from deforested or degraded peatlands. If the soil carbon pool is to be included in country strategy to receive credits for reducing emissions from forest land, the related monitoring component should be established from the beginning to provide the required accuracy for estimation and reporting. For other countries, the monitoring of emissions and removals from all carbon pools and all categories is certainly encouraged in the longer-term but maybe of lower priority and require smaller amount of resources in the readiness phase. This approach is supported by the current IPCC guidance which already allow a cost-efficient use of available resources, e.g. the concept of key categories[115] indicate that priority should be given to the most relevant categories and/or carbon pools. This flexibility can be further expanded by the concept of conservativeness[116]".

The analysis and use of existing data is most important for the estimation of historical changes and for the establishment of the reference emission levels. Limitations of existing data and information may constrain the accuracy and completeness of the LULUCF inventory for historical periods, i.e. for lack of ground data. In case of uncertain or incomplete data, the estimates should follow, as much as possible, the IPCC reporting principles and should be treated conservatively with motivation to improve the monitoring over time. The monitoring and estimation activities for the historical period should include a process for building the required capacities within the country to establish the monitoring, estimation and reporting procedures as a long-term term system. Consistency between the estimates for the reference level and those produced in the assessment period is essential. The existing gaps and known uncertainties of the

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[115] Key categories are sources/sinks of emissions/removals that contribute substantially to the overall national inventory (in terms of absolute level and/or trend). According to the IPCC-GPG, key categories should be estimated at higher Tiers (2 or 3), which means that Tier 1 is allowed for non-key categories.

[116] Conservativeness is a concept used by the provisions of the Kyoto Protocol (UNFCCC 2006). In the REDD+ context, conservativeness may mean that - when completeness or accuracy of estimates cannot be achieved - the reduction of net emissions should not be overestimated, or at least the risk of overestimation should be minimized (see section 2.8)

historical data should be addressed in future monitoring efforts as part of a continuous improvement and training program.

4.3 CAPACITY GAPS AND COST IMPLICATIONS

There are several categories of costs to be considered for countries to engage in REDD+ including opportunity costs, and costs for transactions and implementation. Monitoring, reporting and verification of forest carbon are primarily reflected in the transaction costs, i.e. proof that a REDD+ activity has indeed achieved a certain amount of emission reductions and is suitable for compensation. The resources needed for monitoring are a smaller component considering all cost factors for REDD+ implementation in the long-term, but are rather significant in the readiness phase since many countries require the development of basic capacities.

Estimating the costs for REDD+ monitoring has to consider several issues that depend on the specific country circumstances. First, there is a difference in the cost structure for developing and establishing a monitoring system versus the operational implementation. For countries starting with limited capabilities significantly larger amount of resources are anticipated, particularly for monitoring historical forest changes and for the establishment of the reference level and near term monitoring efforts. In some cases it is assumed that readiness costs require significant public investment and international support, while all implementation costs (including the verification of compliance) should be ideally covered by carbon revenues (Hoare et al., 2008). Secondly, different components of the monitoring system, i.e. forest area change monitoring and measurements of carbon stock change have different cost implications depending on what method is used and which accuracy is to be achieved. For example, an annual forest area change monitoring combined with Tier 3 carbon stock change maybe more costly but less accurate than using 5-year intervals for monitoring forest area and carbon stock change on Tier 2 level.

Specific information on the costs for REDD+ are rare but experiences of estimates in this section is based on a number of resources:

- Operational national forest monitoring examples (i.e. from India and Brazil).
- Ongoing forest monitoring programs involving developing countries ranging from local case studies to global assessment programs (i.e. from FAO activities).
- Idea notes and proposals submitted by countries to the Worldbank Forest Carbon Partnership Facility (FCPF).
- Scientific literature documented in REDD-related monitoring and case studies.
- Expert estimates and considerations documented in reports (i.e. consultant reports) and international organizations and panels.

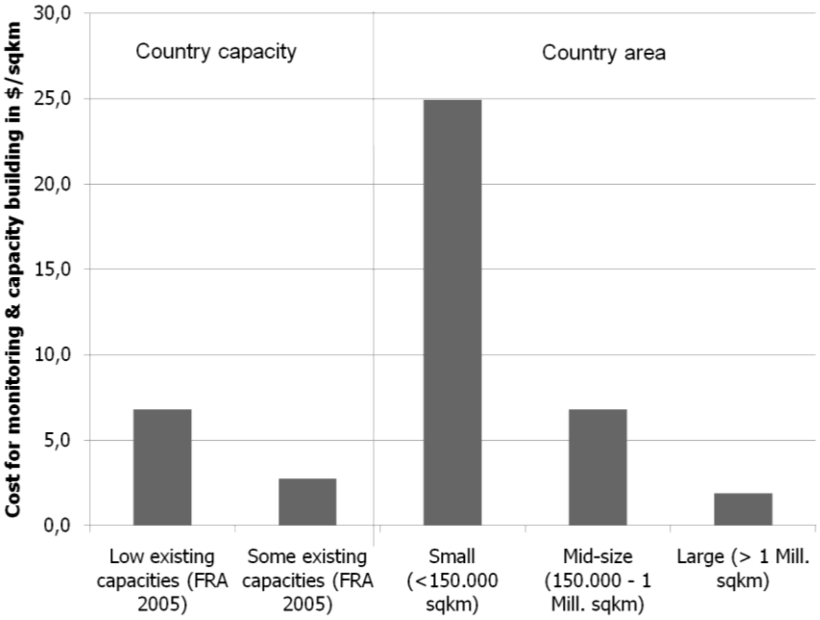
There are number of cost estimates for REDD+ monitoring. For example, Hoare et al. (2008) estimate between 1-6 Mill US$ for the establishment of the REL and the monitoring system per country. This assessment is largely based on work by Hardcastle et al. (2008) that estimate cost for monitoring for different country circumstances building on knowledge of existing capacities. Operational monitoring costs are often provided as per area unit numbers (i.e. see examples from India and Brazil). Building upon these efforts, the aim of the following section is not to provide specific number since they largely vary based on country circumstances and REDD+ objectives.

4.3.1 Importance of monitoring for establishing a national REDD+ infrastructure

Costs for monitoring and technical capacity development will be an important component in the REDD+ readiness phase. Understanding the historical forest change processes is fundamental for developing a national REDD+ strategy based on current forest and environmental legislation. Establishing a national reference scenario for emissions from deforestation and forest degradation based on available historical data is an initial requirement. This effort involves capacity development to establish a sustained national system for monitoring and reporting emissions and removals from forest land in the long-term.

The distribution of costs for monitoring activities (done by the country itself or with help from international partners), and costs for capacity development are related to the existing country capacities and country size. Figure 4.3.1 shows an assessment of 15 Readiness Plan Idea Notes (R-Pins) submitted to the World Bank Forest Carbon Partnership Facility that have provided budget details. The combined cost of monitoring and capacity building activities ranges from 2-25 US$ per sq km depending on the land area and existing capabilities. Countries with low existing capacity indicated more required resources, with a larger proportion towards capacity building. The monitoring efficiency for small countries is usually challenged since an initial amount of base investments are equally required for all country sizes, i.e. a minimum standard for operational institutional capacities, technical and human resources, and expertise in reporting.

Figure 4.3.1. Indicative costs per km^2 for monitoring and capacity building as part of the proposed Worldbank FCPF readiness activities. The graph shows median values based on 15 R-PIN's separated by country capacities and land area. Countries were considered to have low capacities if they did not report either forest area change based on multi-date data or data on forest carbon stocks for the last FAO FRA (FAO, 2006).



4.3.2 Planning and design

Planning and design activities should result in a national REDD+ monitoring framework (incl. definitions, monitoring variables, institutional setting etc.), and a plan for capacity development and long-term improvement and the estimation anticipated costs. Fundamental for this process is the understanding of relevant national actors about the international UNFCCC negotiations on REDD, the status of the national REDD+ implementation activities, knowledge in the application of IPCC LULUCF good practice guidance and expertise in terrestrial carbon dynamics and related human-induced changes. Resources for related training and capacity building are required to participate in or organize dedicated national or regional workshops or to hire international consultants or experts. Some initiatives are already offering capacity development workshops to countries for this purpose, i.e. as part of GTZ's CD-REDD+ program (http://unfccc.int/files/methods_science/redd/technical_assistance/training_activities/application/pdf/cd_redd_concept_note.pdf).

4.3.3 Institutional capacities

Efficient and sustainable organizational capacity is required as the country moves into the Readiness phase, to establish and operate a national forest carbon MRV program. Thus, there are some requirements for a national institutional framework from an MRV perspective:

- **Coordination** - A high-level national coordination and cooperation mechanism linking between forest carbon MRV and national policy (for REDD+), also specifying and overseeing the different roles and responsibilities, and co-benefits with other monitoring efforts (e.g., "the National System").
- **Measurement and monitoring** - protocols and technical units for acquiring and analyzing of different types of forest carbon related data on the national and sub-national level.
- **Reporting** - a unit responsible for collecting all relevant data in central database for national estimation and international reporting using the IPCC GPG, including uncertainty assessment and improvement plan.
- **Verification** - an independent extra-national framework for verifying the long-term effectiveness of REDD+ actions on different levels and by different actors.

Different actors and sectors need to be working in coordination to make the monitoring system efficient in the long-term. Sustainability considerations are an important principle in setting up an institutional framework for an MRV system. At a minimum, a country should consider maintaining the following institutions with clear definition of roles and responsibilities:

- National coordination and steering body or advisory board, including a national carbon registry.
- Central carbon monitoring and reporting authority.
- Forest carbon measurement and monitoring implementation units.

The resources required for setting up and maintaining institutional capacities depend on several factors. Some countries may perform most of the acquisition, processing and analysis of data through their agencies or centralized units; others may decide to build upon outside partners (i.e. contractors, local communities or regional centers), or involve communities.

It is important to note that the institutional framework needs to link MRV of actions and MRV of support. Any compensation for REDD+ actions should be bound to a way of measuring the positive impact in the long-term for both actions and support. A specific sub-national implementation activity will need to be assessed in terms of the amount of forest carbon preserved (measurement), provide this data to the national level so it can be included in the national reporting system, and will need to be verified in terms of leakage (through systematic national monitoring), and permanence (long-term of assessment of compliance). The institutional framework for MRV of support should be directly linked to these requirements, so any compensation transactions would provide incentives to all actors and reflect the different roles and responsibilities within the country. Thus, the national institutional infrastructure needs to provide the foundation for countries to be inclusive and effective in setting up their REDD+ MRV and consider the diverse set of needs and requirements:

Efficiency - using transparent, consistent and cost-effective data sources and procedures, sets up an institutional infrastructure and establishes sustained capacities within the country that meet its national and international REDD+ requirements and enables to report forest carbon changes using the IPCC GPG in the long-term.

Effectiveness - supports and is driven by the development and implementation of a national REDD+ policy and its priority areas of action.

Equity - integrates local measurements, national-level monitoring estimation and international guidance, and supports independent international review, to ensure participation and transparency among different actors involved.

The size and amount of resources required for setting up and maintaining institutional capacities depend on several factors. Some countries will perform most of the acquisition, processing, and analysis of data by their agencies or centralized units; others may decide to build upon outside partners (i.e. contractors, local communities or regional centers). Although a minimum amount of institutional capacities is required even for small countries, larger countries will need to invest in a more complex and more expensive organization structure.

4.3.4 Cost factors for monitoring change in forest area

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 quality observations. The only practical approach for such monitoring systems is through interpretation of remotely sensed data supported by ground-based observations. The use field survey and inventory type data for national level estimation of activity is performed by several Annex I Parties (Achard et al., 2008). However, the use of satellite remote sensing observations (in combination with field observations for calibration and validation) for consistent and efficient monitoring of forest area change using Approach 3 of the IPCC GPG can be assumed to be the most common option for REDD+ activities in developing countries; in particular for countries with limited information for the historical period.

The implementation of the satellite-based monitoring system includes a number of cost factors:

- ❑ Satellite data including data access and processing
- ❑ Soft/Hardware and office resources (incl. satellite data archive)
- ❑ Human resources for data interpretation and analysis
  - Monitoring in readiness phase
  - Operational monitoring
- ❑ Accuracy assessment
- ❑ Regional cooperation

For countries without existing operational capacities the costs for developing the required human capacities will need to be considered. In the establishment phase, the work of national and international experts includes the following activities:

- ❑ Assessment and best use of existing observations and information.

- ☐ Specify a methodology and operational implementation framework for monitoring forest area change on a national level.
- ☐ Perform analysis of historical satellite data for establishing reference emission levels.
- ☐ Develop understanding of areas affected by forest degradation and provide assessment on how to monitor relevant forest degradation processes.
- ☐ If required, set up system for real-time deforestation monitoring (i.e. including detection of forest fires and areas burnt).
- ☐ Complete recruitment and provide training to national team to perform monitoring activities.
- ☐ Complete an accuracy and error analysis for estimates from the historical period.
- ☐ Perform a test run of the operational forest area change monitoring system.

Once a monitoring system is consolidated in the readiness phase, the continuous monitoring operation produces annual operational costs for the different components of the system mentioned in Table 4.2.1. For example, if a country decides to monitor forest area change using its own resources and capacities the annual cost for human resources maybe on the order 3 to 4 times smaller than for the establishment phase (Hardcastle et al. 2008).

The resources required for operational monitoring depend on the size of the area to be mapped each year and the thematic detail and accuracy to be provided. In general, the smallest implementation unit of three skilled technicians should be sufficient to perform all operations for the consistent and transparent monitoring of forest area change for small to medium country sizes in 2- to 3-year time intervals. Costs for data and human resources will increase if an annual forest area change monitoring interval is performed.

4.3.5 Cost factors for monitoring change in carbon stocks

Estimates of carbon stocks in aboveground biomass of trees are frequently obtained by countries from various sources (Table 4.2.1), and for other forest carbon pools default data (for use with Tier 1 approach) provided by in the IPCC good practice guidance for LULUCF are normally used.

Growing stock volume collected in conventional forest inventories can be used to produce biomass values using methods in the IPCC good practice guidance for LULUCF or other more specific methods proposed by some authors in line with them. The stratification by forest types and management practices, for example, mature forest, intensely logged, selectively logged, fallow, could help to achieve more accurate and precise results. Many developing countries use some country-specific inventory data to estimate carbon stocks of forests (but often, they use factors from the IPCC to convert volume to biomass); this could be seen to be equivalent to a low level Tier 2 for emission factors as defined in the IPCC good practice guidance for LULUCF.

However, conventional forest inventories are often done in forests considered to be productive for timber harvesting, often do not include forests that have little commercial timber, and measurements may have not been stratified and acquired for carbon stock assessments. Also, as Table 4.2.1 shows, many inventories are old and out of date and may not be the forests undergoing deforestation.

Compilation of data from ecological or other permanent sample plots may provide estimates of carbon stocks for different forest types but are subject to the design of particular scientific studies and thus tend to produce unreliable estimates over large forest areas.

Before initiating a program to monitor carbon stocks of land cover classes, certain decisions will need to be made concerning the following key factors that directly impact the cost of implementing a monitoring system:

- ☐ What level of accuracy and precision is to be attained—the higher the targeted accuracy and precision (or lower uncertainty) of estimates of carbon stocks the higher the cost to monitor.
- ☐ How to stratify forest lands—stratification into relatively homogeneous units of land with respect to carbon stocks and their dynamics lowers the cost as it reduces the number of sample plots.
- ☐ Which carbon pools to include—the more carbon pools included the higher the cost.
- ☐ At what time intervals should carbon stocks in specific areas be monitored over time; the shorter the time interval, the higher the cost and specific areas targeted for REDD+ implementation activities may require more frequent measurements.

Estimation of carbon stocks on the land needs sampling, which is process by which a subset is studied to allow generalizations to be made about the whole population or area of interest. The values 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.

The accuracy and precision of ground-based measurements depend on the methods employed and the frequency of collection. If insufficient measurement effort is expended, then the results will most likely be imprecise. In addition, estimates can be affected by sampling errors, assessment errors, classification errors in remote sensing imagery and model errors that propagate through to the final estimation.

Total monitoring costs are dependent on a number of fixed and variable costs. Costs that vary with the number of samples taken are variable costs, for example, labor is a variable cost because expenditure on labor varies with the number of sample plots required. Fixed costs do not vary with the number of sample plots taken. The total cost of a single measurement event is the sum of variable and fixed costs.

There are several variable costs associated to ground based sampling in forest that could include or depend on:

a) labor required which depends on sampling size;

b) equipment use and rental;

c) communication equipment use and rental;

d) food and accommodation;

e) field supplies for collecting field data; and

f) transportation and analysis costs of any field samples (e.g. biomass samples).

Variable costs listed in categories (a) to (d) in paragraph above will vary with the number of samples required; the time taken to collect each sample and the time needed to travel from one sample site to another (e.g. affected by the size and spatial distribution of the area being contiguous or non-contiguous), as well as, by the number of forest carbon pools required. These are the major factors expected to influence overall sampling time. At a national scale, it is likely that travel time between plots could be as long as or longer than the actual time to collect all measurements in a plot. Costs listed in sub-bullets (e) and (f) are only dependent on the number of samples required.

The cost for deriving estimates of forest carbon stocks based on field measurements and sampling depends on the targeted precision level. The higher the level of precision the more plots are needed, similar precision may require more or less samples depending on the variability of the carbon stocks in the plot. A measure of the variability commonly used is the coefficient of variation of the carbon stock estimates, the higher the coefficient of variation the more variable the stocks and the more plots needed to achieve the same level of precision.

Stratification of forest cover can increase the accuracy and precision of the measuring and monitoring in a cost-effective manner (see section 2.2). Carbon stocks may vary substantially among forest types depending on physical factors (e.g., climate types, precipitation regime, temperature, soil type, and topography), biological factors (tree species composition, stand age, stand density) and anthropogenic factors (e.g. disturbance history and logging intensity).

4.3.6 Spatial data infrastructure, access and reporting procedures

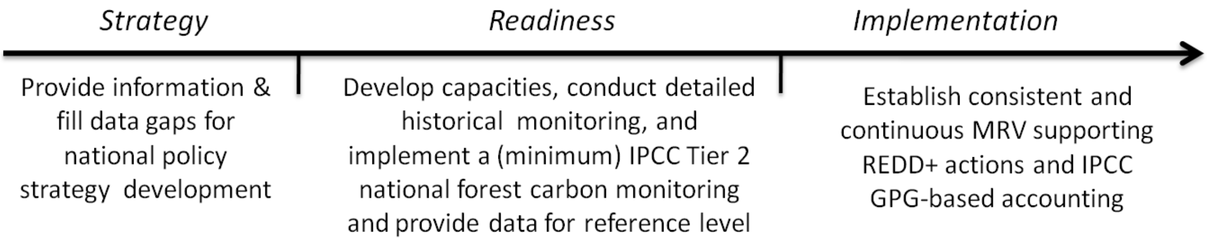
A centralized spatial data infrastructure should be established to gather, store, archive, and analyze all required data for the national reporting. This requires resources to establish and maintain a centralized database and information system integrating all required information for LULUCF. There is need to establish a data infrastructure, incl. information technology (suitable hard/software), and for human resources to generate, manipulate, apply, and interpret the data, as well as capability to perform the reporting and accounting using the UNFCCC guidelines. There should also be consideration of data access procedures for (spatially explicit) information in transparent form.

4.4 LINKING MONITORING AND POLICY DEVELOPMENT

REDD+ assumes that changes in forest carbon stocks from direct or indirect human activities have an impact on the climate and should be accounted for. Considering the variety of country circumstances different emphasis will be given to the various processes impacting forest carbon (i.e. land use change causing deforestation versus selective logging or shifting cultivation) in both the context of policy and MRV. The difference between the national and international REDD+ MRV requirements and the current capacity status is diverse. Country specific capacity development pathways will need to be based on these requirements that will be further elaborated in the next sections.

Each country will have to develop its MRV system to meet its specific package of REDD+ actions, while at the same time tailoring its selection of actions to what is feasible for it as regards MRV. However, some general suggestions and guidance can be provided. Figure 4.4.2 lists a set of essential steps each country has to consider in evolving the policy and technical issues in conjunction. The phase of strategy development and readiness maybe addressed rather quickly if a country has a suitable set of existing data and capacities. In contrary, some countries may have to first derive initial datasets to provide basic understanding to what extend drivers are active and what their forest carbon impact is and how policies can be defined and implemented to affect the drivers and processes. Thus, MRV does include a component of analysis and assessment that is essential to make use of the acquired data and information in a policy context, i.e., as suggested in the term MARV (Measurement, Assessment, Reporting and Verification).

Figure 4.4.2. MRV objectives for different phase of REDD+ participation.



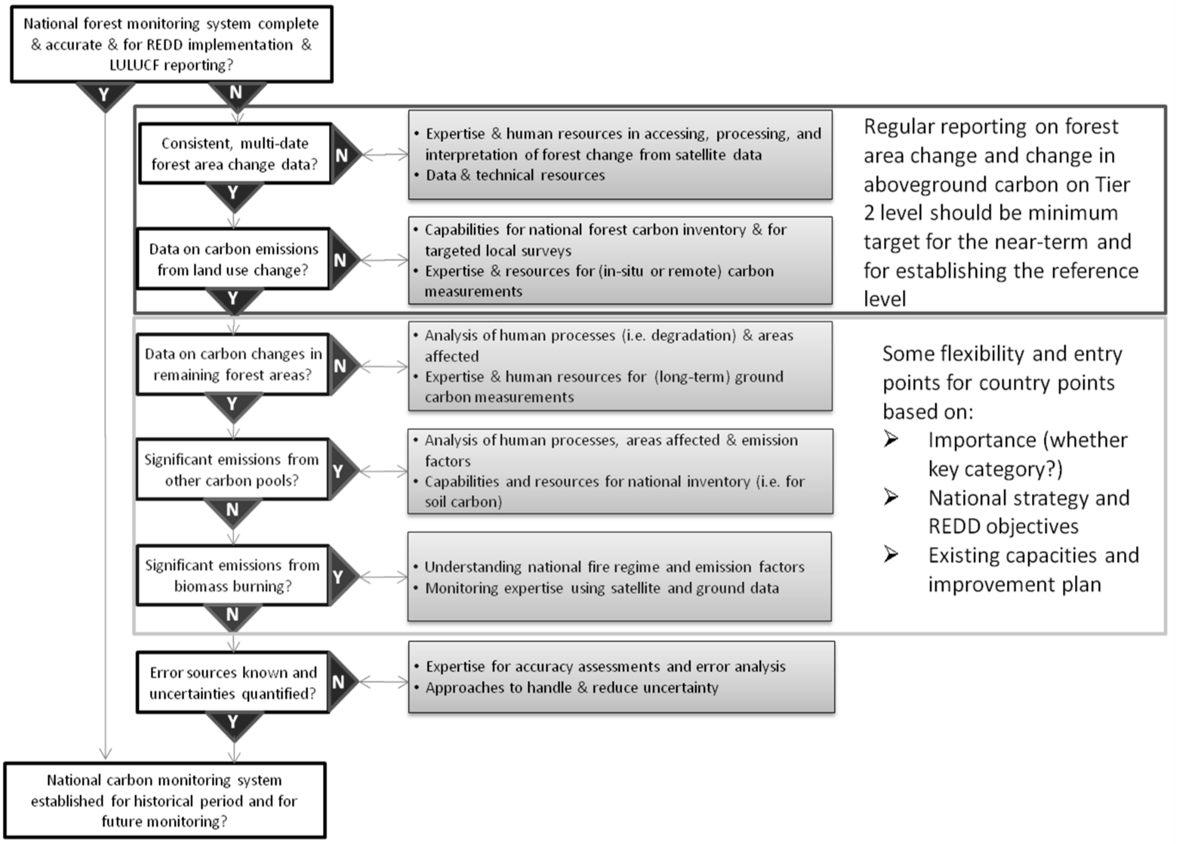
International policies and MRV concepts reflect an emission-oriented concept focusing on carbon impacts. National policy development should, however, take a more driver-oriented perspective assuming that successful national policies will need to target the key causes and processes that alter forest carbon on the ground. For an MRV roadmap, what is important is an understanding of the drivers and processes active, whether sufficient data are available to assess their importance (carbon impact), and what policies could positively affect the processes to achieve REDD+ objectives. The results can be summarized in a framework suggested in Table 4.4.1.

Table 4.4.1. Conceptual link between national REDD+ policy opportunities and monitoring requirements based on assessment of processes affecting carbon stocks.

Processes and drivers that affect forest carbon stocks	**Current data and monitoring capacities**	**Importance (carbon impact on national level)**	**Suggested activity to fill monitoring capacity/data gap**	**REDD+ opportunities & anticipated policies to encourage or discourage process**
Forest conversion for expansion of agriculture	Sample-based national forest inventory for two points in time	Significant areas affected nationally and large carbon emissions per ha	Assessment using remote sensing-based forest area change and forest carbon inventory data	Protection of existing forests and use of non-forested land for agriculture
Selective logging for timber and fuel in native forests remaining forest	Harvest estimates, and concessions areas by companies and forestry department	Significant areas affected and low emission per ha	Gather existing data on area and harvest data, convert to carbon emissions, further long-term case studies	Shifting towards low impact logging and sustainable forest management
Clear-fell and selective harvesting in forest plantations	Harvest estimates, concessions areas and growth rates by companies and forestry department	Some areas nationally, may act as C-sink or source depending on previous land use and harvest cycles and intensity	Gather data on national level and evaluate data with remote sensing assessment, conversion of existing estimates into carbon values	Encourage A/Reforestation of non-forested land, low impact harvesting and sustainable forest management
Other processes identified				

This type of assessment will help develop priorities in terms of both national policies and monitoring requirements (indeed, the decisions on national REDD+ strategies needs to proceed in parallel with the MRV procedures). One of the most fundamental questions is whether sufficient data are available to understand the recent forest carbon impact of specific processes or whether further studies are required in order to select those actions which are likely to be successful. The long-term MRV needs may then be defined in greatest detail and accuracy for the drivers and processes causing the majority of forest carbon stock changes, and these drivers should be the ones particularly addressed in the REDD+ strategy and implementation activities. For this purpose, the IPCC GPG provides some flexibility by focusing on key categories. Key categories are sources of emissions and removals that contribute substantially to the overall national inventory (in terms of absolute level and/or trend). Key categories or pools should be measured in more detail and certainty and estimated using higher Tiers (Tier 2 or 3), which means that Tier 1 (IPCC default data) may be used for non-key categories or pools.

Figure 4.4.3. Flowchart for scoping detail of national monitoring system linking key components and required capacities.



The activities indicated for the readiness phase (Figure 4.4.3) include acquiring of historical data with the goal of achieving a minimum of an IPCC Tier 2 national carbon monitoring, as well as providing all data and information needed for establishing the reference level. Monitoring of historical and future changes in forest carbon should be done on a continuous and consistent basis. The historical assessment would be a one-time consolidated effort as part of the readiness phase. However, the type and quality of monitoring data available for previous years may be limited, in particular with respect to available field data. The future monitoring may choose from different options and can incorporate the specific REDD+ requirements.

Figure 4.4.3 provides some guidance on what capacities may need to be established for this purpose; assuming that Tier 2 monitoring in the aboveground vegetation carbon pool for forest area changes is considered to be the minimum requirement. The level of detail for the other components depends on a number of factors that are country specific. Depending whether some carbon stock changes are significant (key category) or if some activities are particular targeted from the REDD+ policy (i.e. shifting from conventional logging to sustainable forest management) more investment in MRV capacities and resources are needed beyond the minimum requirement.

A national REDD+ strategy needs to encourage specific local implementation actions. In this context, a national carbon monitoring system would reflect more detail and accuracy in these action areas, and, more specifically, a national estimation and reporting system needs to include sub-national or action area measurement plans. Thus, a suitable national monitoring strategy should include:

- ❑ A national monitoring, estimation and accounting system and a sub-national measurement plan addressing change in forest carbon and the key drivers of change in these areas.
- ❑ A national stratification allowing all (area based) REDD+ and REDD+ implementation activities to be measured with a suitable degree of certainty (higher intensity in REDD+ and REDD+ action areas, lower density systematic monitoring in the rest). Such a national stratification may be based on forest carbon density and on types of human activities and REDD+ interventions.
- ❑ A system of sub-national reference levels - suitable for large countries (e.g. Indonesia) and related reporting and accounting for carbon balance, displacement of emissions and permanence.
- ❑ A systematic component that helps sub-national activities to show their effectiveness and to understand leakage and additionality within the country. It would also provide a framework for continuous monitoring to verify permanence.
- ❑ Reference to existing pilot projects, which may be useful in:
    - providing measurements and information on forest change processes;
    - quantifying REDD/REDD+ achievements (e.g. through centralized carbon registry); and
    - demonstrating involvement of communities and key actors.

With regard to pilot projects, in several countries REDD+ demonstration projects have already generated some experience and it may be possible to draw lessons from these regarding MRV. However, there are considerable differences between project and national approaches. Firstly, while the data collected in association with pilot projects may give useful indications of the likely gains and losses of carbon associated with different types of management activities, monitoring at project level often brings high costs related to dealing with leakage and additionality, and to other transaction costs involved; in a national approach, apart from benefits of economies of scale, many of these problems may be circumvented. Secondly, existing pilot projects are local and often specialized in scope - for example located in areas with limited conflicts (e.g. related to land tenure) or in areas of high-risk, high-carbon forests - and addressing only a small number of drivers. Broader issues that are important for REDD+ effectiveness (e.g. relating to national regulatory frameworks, addressing land use policy, and involving the agriculture and energy sector), are not taken into account, nor the requirements of national MRV systems and baselines. A potential issue in up-scaling from project scale to a national system will be to solve incompatibilities between existing definitions of forest. In particular in a number of countries, secondary and degraded woodlands are not included in national forest statistics. Under a REDD+ national accounting system, these differences would have to be adjusted.

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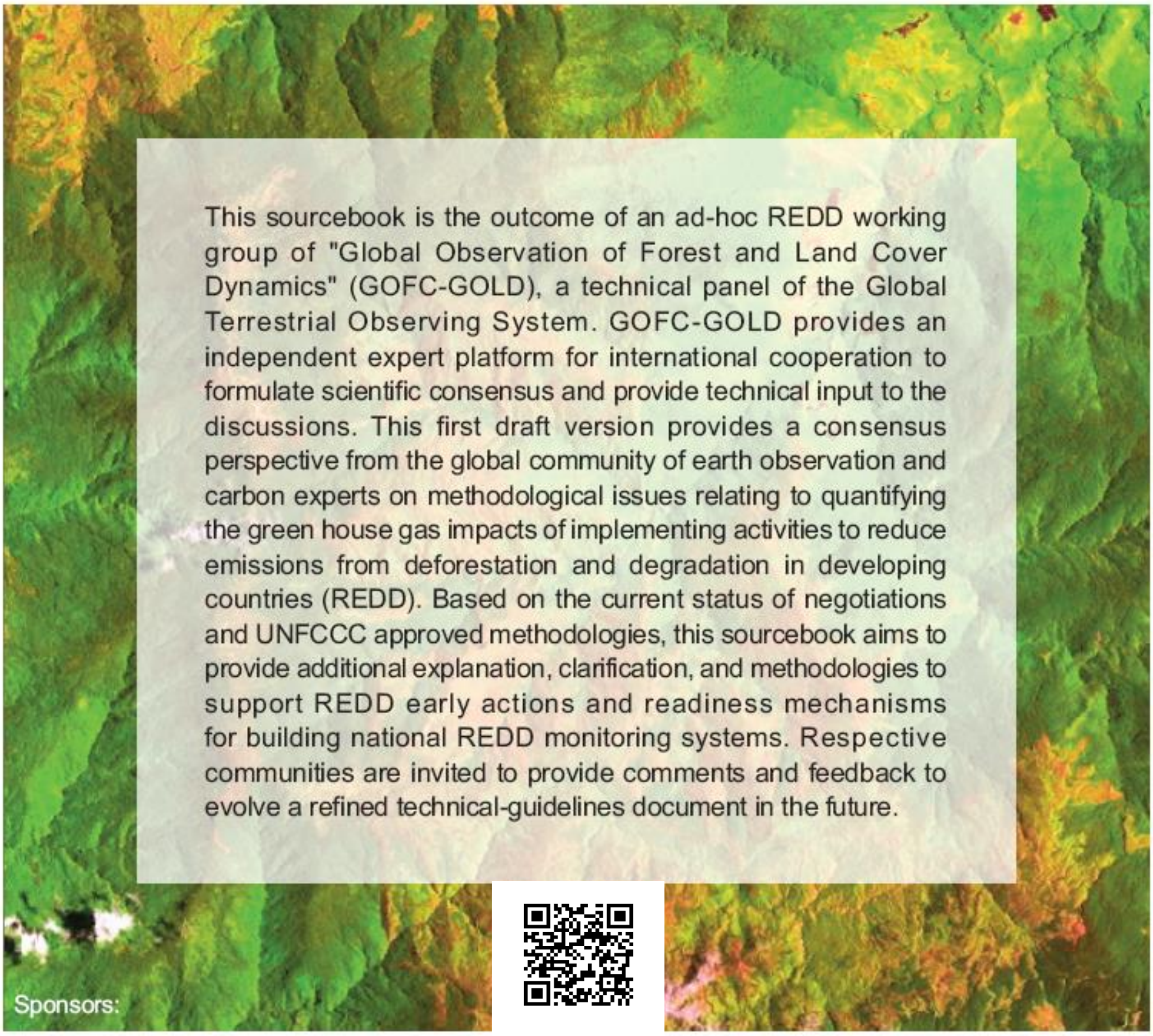

This sourcebook is the outcome of an ad-hoc REDD working group of "Global Observation of Forest and Land Cover Dynamics" (GOFC-GOLD), a technical panel of the Global Terrestrial Observing System. GOFC-GOLD provides an independent expert platform for international cooperation to formulate scientific consensus 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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