REDD+ MEASUREMENT, REPORTING AND VERIFICATION (MRV) MANUAL

FOREST CARBON, MARKETS AND COMMUNITIES (FCMC) PROGRAM

OCTOBER 2013

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The US Agency for International Development (USAID) has launched the Forest Carbon, Markets and Communities (FCMC) Program to provide its missions, partner governments, local and international stakeholders with assistance in developing and implementing REDD+ initiatives. FCMC services include analysis, evaluation, tools and guidance for program design support; training materials; and meeting and workshop development and facilitation that support US Government contributions to international REDD+ architecture.

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The authors' views expressed in this publication do not necessarily reflect the views of the United States Agency for International Development or the United States Government.

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ACRONYMS AND ABBREVIATIONS

ACR	American Carbon Registry
AD	Activity data
AGB	Aboveground biomass
BCEFs	Biomass Conversion and Expansion Factors
BRDF	Bi-directional Reflectance Distribution Function
BURs	Biennial Update Reports
USAID	United States Agency for International Development
CH4	Methane
CI	Conservation International
CI	Confidence interval
CIFOR	Center for International Forestry Research
CO2	Carbon dioxide
COP	Conference of the Parties
CV	Coefficient of variation
DBH	Diameter at breast height
DTs	Decision trees
EFDB	IPCC's Emission Factor Database
EFs	Emission factors
EPA	Environmental Protection Agency
FAO	Food and Agricultural Organization
FAS	Fire Alert System
FCMC	USAID's Forest Carbon, Markets and Communities Program
FCPF	Forest Carbon Partnership Facility
FIRMS	Fire Resource Management Systems
FSI	Forest Survey of India
FUNCATE	Brazil's Foundation of Space Science, Applications and Technology

GEF	Global Environmental Facility
GHG	Greenhouse gas
GIS	Geographic Information System
GLAS	Geoscience Laser Altimeter System
GOFC-GOLD	Global Observation of Forest and Land Cover Dynamics
GPG 2000 Inventories	IPCC's Good Practice Guidance and Uncertainty Management in National Greenhouse Gas
GPG-LULUCF	IPCC's Good Practice Guidance for Land Use, Land-Use Change and Forestry
GPS	Global Positioning System
ICA	International Consultation and Analysis
ICESAT	Ice, Cloud and Land Elevation Satellite
IDEAM	Colombia's Institute for Hydrology, Meteorology and Environmental Studies
ILUA	Integrated Land Use Assessment
IMAZON	Amazon Institute of People and the Environment
INPE	Brazil's National Space Research Institute
IPCC	Intergovernmental Panel on Climate Change
KCA	Key Category Analysis
LDCM	Landsat Data Continuity Missions
LEDAPS	Landsat Ecosystem Disturbance Adaptive Process System
LiDAR	Light Detection and Ranging
MADS	Colombia's Ministry of Environment and Sustainable Development
MCT	Brazil's Ministry of Science, Technology and Innovation
MMU	Minimum mapping unit
MRV	Measurement, Reporting and Verification
MSS	Multi-spectral scanner
NAMAs	Nationally Appropriate Mitigation Actions
NCs	National communications
NGGIP	IPCC's National GHG Inventories Program
NGOs	Non-governmental organizations
NNs	Neural networks
NO2	Nitrogen dioxide
NRT	Near-real time

PCA	Principal Components Analysis
QA/QC	Quality assurance/quality control
QUICC	Quarterly Indicator of Cover Change
RADAR	Radio Detection and Ranging
REDD+	Reducing emissions from deforestation and forest degradation
REL	Reference emission level
RL	Reference level
SAD	IMAZON's Deforestation Alert System
SAR	Synthetic Aperture RADAR
SBSTA	UNFCCC's Subsidiary Body on Scientific and Technical Advice
SINA	Colombia's National Environment System
SMA	Spectral Mixture Analysis
TM	Thematic Mapper
UN-REDD	United Nations REDD+ Programme
UNFCCC	United Framework Convention on Climate Change
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
VCS	Verified Carbon Standard
WRI	World Resources Institute

1.0 INTRODUCTION

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1.1 PURPOSE, SCOPE AND STRUCTURE

The purpose of this manual is to provide an overall review of data, models, techniques and accounting methods that should, or could, be part of a Measurement, Reporting and Verification (MRV) program for reducing emissions from deforestation and forest degradation (REDD+). This is in the context of REDD+ as a mechanism within the United Nations Framework Convention on Climate Change (UNFCCC). This manual is intended to inform policy makers on REDD+, as well as implementers of MRV at the national-level.

1.1.1 Audience

This manual is intended for multiple audiences. First, it is intended for those in charge of planning and developing a MRV system within a national or sub-national agency. While these individuals may not conduct specific MRV activities such as field work, data processing, analysis and reporting themselves, there is a need for them to understand what is involved in terms of staff time, funds, expertise, capacity building, accuracy issues, and options for different techniques and methods. It is important that these individuals have a broad view of all aspects involved in a MRV system in order to envision a structure within the agency, as well as an understanding of the range of MRV components in order to engage in informed discussions about staffing and equipment needs and the impacts that choices, regarding the different techniques and data have on the final greenhouse gas (GHG) accounting. They should also have a fundamental knowledge of the language and concepts of MRV in order to engage with consultants, know what questions to ask, and critically compare the varying advice they may receive.

This manual is also intended for managers and technicians who are designing a sub-component of a MRV system, or are involved in MRV at sub-national levels including sub-national jurisdictions or site-level initiatives. It is intended to assist these individuals in envisioning such a design, as well as understanding the broader context of their sub-component. For the sub-national jurisdictional case, one can assume that the arrangements and requirements are similar, yet at a smaller scale, and coordination with the national government will be very important. Even if the overall MRV process occurs at the level of a sub-national jurisdiction, some aspects of the MRV system may still be conducted nationally to lower overall costs and promote standardization.

As mentioned, those working at the sub-national level will find the information in the following chapters especially relevant. The Verified Carbon Standard (VCS) and the American Carbon Registry (ACR) are examples of programs that serve a supporting role in voluntary carbon markets through registering emission reductions claimed by site-level initiatives. These programs provide methodologies, subject to an approval process by the programs, for the estimation of REDD+ baselines and MRV, as well as approaches to nested REDD+, where accounting and monitoring at different levels can be coordinated. The technical aspects of these methodologies often defer to the Intergovernmental Panel on Climate Change (IPCC) guidelines, especially those related to the definition of land-use classes and the estimation of carbon stocks.

1.1.2 Scope and structure

The manual begins with an overview of the program components needed for a national MRV system, including a discussion of national arrangements required by the UNFCCC (Chapter 2). The following three chapters address Measurement processes, i.e., the GHG Inventories (Chapter 3) and their main inputs, Ground-Based Inventories (Chapter 4), and Land-Use Change assessment (Chapter 5). Chapter 6 covers Reporting and Verification processes.

In addition, three thematic reviews are provided for further information. The first covers the UNFCCC REDD+ negotiations and the role the IPCC has played in providing MRV guidance. The two remaining thematic reviews cover activities that could be part of MRV systems, but are, thus far, only broadly defined and being tested in various countries: community-based MRV and near-real time (NRT) monitoring. A short glossary is provided in the Appendix at the beginning of the manual.

The reader will notice that some chapters are less prescriptive than others. This diversity is a reflection of the present state of science and guidance on these topics. For example, the IPCC guidelines provide specific requirements and reporting formats for GHG inventories. They also provide specific guidance on the measurement of carbon stocks, founded on a long history of field methods in forest inventories. Conversely, while the IPCC provides formats for reporting land-use changes, it provides relatively little specific guidance on how these changes should be estimated. In most cases, remote sensing, primarily via the analysis of digital data acquired by satellites, is needed for national monitoring of land-use changes. Remote sensing is an evolving field with new technologies, and entails a variety of approaches and decision factors worthy of consideration. Chapter 5 provides an overview of steps for selecting a system for monitoring land-use change.

1.2 BACKGROUND

1.2.1 Reducing Emissions from Deforestation and Forest Degradation (REDD+)

Spanning approximately 625 million hectares, the world's tropical forests are rich in natural resources. Tropical forests contain as much as 50 percent of the species on the earth in less than 5 percent of the earth's land area. Additionally, these forests provide a wide range of ecosystem services including timber, fuel wood, water purification, and cultural and religious values. These benefits are crucial to the more than 50 million people who live in tropical forests and the many millions of others who are indirectly dependent on these forest services. In addition, the world's tropical forests help regulate the climate by sequestering and storing 375 billion metric tons of carbon, an ecosystem service of increasing importance as concerns about human induced climate change grow.

The planet, however, is currently losing 7.3 million hectares of forest per year. This rampant deforestation has serious implications for biodiversity, rural communities dependent on forests for food and income, and the global climate. Deforestation releases significant amounts of carbon dioxide (CO2) into the atmosphere each year. One study by van de Werf et al., 2009, estimated that approximately 12 percent of global CO2 emissions resulted from deforestation in 2009, for example.

Deforestation in the tropics is a major contributor to these emissions and the loss of biodiversity. However, many tropical forested countries lack up-to-date, accurate information on forest cover, carbon content changes occurring in their forests, and drivers of these changes. And, although these countries often have adequate forest policies, they often suffer from weak forest law enforcement and governance which result in over-exploitation of forests and a disregard for the livelihood of local people.

Efforts to provide payments for ecosystem services may create incentives for curbing deforestation and, if effective, help address the needs of forest-dependent communities. These efforts include the REDD+ mechanism, first termed Reduced Emissions from Deforestation and forest Degradation in developing countries (REDD) of the UNFCCC. At the Conference of the Parties (COP) 13 in Bali, Indonesia in 2007,

Box 1.1: The Forest Carbon, Markets and Communities (FCMC) Program

The US Government (USG) pledged $1 billion in "fast-start financing" for 2010 to 2012 to assist countries to develop and implement REDD+ plans that contribute to sustainable livelihoods, protect biodiversity, and respect the rights of Indigenous Peoples, women, the poor, and vulnerable populations. The US Agency for International Development (USAID) has been leading the implementation of REDD+ activities, with funding allocated through the sustainable landscapes pillar of its global climate change program. In response to the demand for technical contributions for enhancing the international framework for REDD+ and for technical assistance in implementing projects and programs related to REDD+, USAID launched the Forest Carbon, Markets and Communities (FCMC) program (2011-2015) to provide its missions, partner governments, local and international stakeholders with technical assistance in developing and implementing integrated REDD+ initiatives.

FCMC is building technical capacity by developing tools and training that support USG contributions to the international REDD+ architecture. The technical competencies provided by FCMC present an integrated approach to address social and environmental soundness; low emissions development strategies; measurement, reporting, and verification; and finance and carbon markets.

The MRV Task within FCMC focuses its efforts on building capacity on protocols linked to REDD+. The FCMC team includes Conservation International (CI), the Greenhouse Gas Management Institute and the World Resources Institute (WRI), coordinated under the overall FCMC-lead organization, Tetra Tech.

REDD was expanded to include sustainable forest management, conservation of forests and enhancement of carbon stocks. This broader definition is referred to as REDD+. The UNFCCC Bali Action Plan (2007), which was later reinforced as the "Cancun Agreements," demonstrated increased willingness for industrialized countries and donors to pay for projects and policies that reduce deforestation in developing countries. The willingness for international support is further demonstrated by the launch of programs such as the Forest Carbon Partnership Facility, and the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation (UN-REDD), as well as several bilateral efforts. The principle of REDD+ and the availability of funds has generated great interest among developing countries. However, to fulfill the requirements for REDD+ (as described in the following chapters) significant capacity building is needed. To build this necessary capacity in preparation for, and anticipation of, REDD+, donors are supporting readiness programs in many countries where improved technical capacity is needed. A major component for REDD+, and a focus of the different initiatives, is training on and development of national systems for MRV.

The UNFCCC has specialized bodies, including the Subsidiary Body on Scientific and Technical Advice (SBSTA), one of two permanent subsidiary bodies to the Convention. In relation to REDD+, the SBSTA provides guidance on technical and methodological elements of REDD+ including MRV and reference levels, and advises the COP and the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol via the provision of timely information on scientific and technological matters as they relate to the Convention or the Protocol.

There are other useful resources available on REDD+ MRV system aspects and options. The Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) MRV Sourcebook, the UN-REDD National Forest Monitoring Systems document, and the Forestry and Forest Products Research Institute's REDD-plus CookBook, all referenced in the following chapters.

As mentioned earlier, another body that has a strong influence on MRV is the IPCC. The IPCC is an intergovernmental body that is open to all member countries of the United Nation Environment Programme (UNEP) (); 195 countries are current members of the IPCC. The IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF), cited in this document, is a key resource and focuses on the overall reporting requirements and detailed criteria for particular aspects of MRV. It serves a key role in providing reporting requirements within the context of the UNFCCC and methodologies for MRV. Much of this document refers to materials produced by the IPCC.

Besides high-level technical guidance bodies, such as SBSTA and the IPCC, there are organizations linked to the UNFCC process that provide funding and carry out pilots projects or country programs to further develop REDD+ understanding. The Global Environment Facility (GEF), an operating financial entity of the Convention, provides financial assistance in accordance with guidance from the COP to non-Annex I Parties through its implementing agencies, the United Nations Development Program (UNDP), UNEP, and the World Bank. Some bilateral agreements also provide financial and technical assistance to many non-Annex I Parties in preparing their national communications. Additional processes at other levels beyond the United Nations also exist. Bi-lateral agreements and support for capacity are underway in a number of countries, as well as a voluntary-carbon market seeking standardization of reliable monitoring to underpin the exchange of carbon credits.

Almost all of these organizations and processes support the idea of REDD+ activities being part of a future pay-for-performance mechanism, and thus emphasize the need for quality MRV. However, the quality of MRV is not always guaranteed, because of:

- *Lack of information*: to evaluate policies and set realistic goals and compensation, forest and land-use information needs to be continuously updated, systematically archived and made available to decision makers so that they can evaluate them in a timely manner. Country-wide data on forest cover change is not gathered in a systematic fashion, and methods and systems for detecting forest clearance and degradation are often absent. Information on forest carbon stocks and flows is absent, and countries cannot account systematically for GHG emissions from land-use sectors.

- *Lack of models for replication*: to guide policy makers in designing policies and programs. There are few existing examples of comprehensive national MRV systems. Mechanisms for sharing data, methodologies, and experiences are insufficient to encourage replication.

- *Lack of capacity*: to gather and utilize information on forest cover and forest carbon. Countries are unable to evaluate the impacts of policy alternatives on forest extent, carbon stocks, and the economy.

- *Lack of transparency*: via sharing data on forests and forest carbon mechanisms to facilitate broad-based civil society participation in REDD+ decision-making. There is no independent monitoring system with the capacity to hold the government accountable for policy decisions.

This document focuses on the information that needs to be gathered, and how to analyze this information (thus reducing both the current lack of information and capacity). A MRV system must also be integrated with the overall development of a REDD+ strategy for a country, as policies must include provisions for ensuring compliance and measuring their impact. This includes coordinating with a country's Nationally Appropriate Mitigation Actions (NAMAs) and associated reporting. Some countries are developing nested REDD+ programs, where REDD+ activities exist at two or more levels, such as site or state levels and national levels. In these cases, MRV must be coordinated across levels to ensure that sub-national MRV systems do not conflict with the national system. Finally, a MRV system should be linked to decision-making and enforcement to better enable adaptive management and policy implementation at the national level.

1.3 REFERENCES

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2.0 INSTITUTIONAL ARRANGEMENTS

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2.1 INTRODUCTION

One of the key prerequisites for Reducing Emissions from Deforestation and Forest Degradation (REDD+) implementation is the establishment of national arrangements, also sometimes referred to as "national systems," that ensure the transparent, comparable, coherent, complete and accurate Measurement, Reporting and Verification (MRV) of greenhouse gas (GHG) emissions and removals from REDD+ activities.

Internationally accepted quality criteria are laid out in the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance and Uncertainty Management for National GHG Inventories (IPCC, 2000), the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF) (IPCC, 2003), and the IPCC 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). According to these guidelines, GHG inventories must be:

- Transparent: There is sufficient and clear documentation so that individuals or groups other than the inventory compilers can understand how the inventory was compiled and can confirm the quality of the data;
- Complete: Estimates are reported for all relevant activities and gases. Where data are missing, their absence should be clearly documented;
- Consistent: Estimates for different inventory years, gases and categories are made in such a way that differences in the results between years and activities reflect real differences in emissions. Inventory annual trends, as far as possible, should be calculated using the same method and data sources for all years and should aim to reflect the real annual fluctuations in emissions and not be subject to changes resulting from methodological differences;
- Comparable: The GHG inventory is reported in a way that allows it to be compared with GHG inventories from other countries; and
- Accurate: The GHG inventory contains neither over nor underestimates, so far as can be judged, and uncertainties have been reduced as much as is possible. This requires undertaking all efforts to remove bias from the inventory estimates.

The three elements of MRV are defined as follows:

Measurement includes both the actual/physical measurement of emissions or removals from forest areas, as well as their calculation, using either simple formulas that rely on the use of land areas and specific emission factors, or complex models that take into account a number of different parameters that affect the release or sequestration of carbon and other GHGs.

Reporting refers to the process of documenting estimates of GHGs and the methodologies used to derive them, as well as other related issues, such quality assurance and quality control (QA/QC) activities, uncertainty estimation, etc.

Verification provides inputs to improve GHG inventories, build confidence in estimates and trends, and help to improve scientific understanding of GHGs. Specific activities include both internal and external checks of the inventory parameters.

In addition to MRV, there is the aspect of **monitoring**. Monitoring is of particular importance for REDD+ activities as it brings together multiple objectives and aims to maximize the total benefits. Monitoring encompasses MRV, governance aspects, as well as the efforts to generate information on the effectiveness of policies and forest management practices as part of REDD+ implementation. In this manual the focus is on MRV; specific monitoring issues are addressed separately.

In the context of this manual, the term national "arrangements," also encompassing sub-national arrangements for specific jurisdictions, is defined as the processes and procedures that codify all relevant elements of a fully operational MRV system covering all lands and activities relevant to REDD+, in a manner that adheres to the IPCC principles and relevant United Nations Framework Convention on Climate Change (UNFCCC) or other guidance.

A key benefit to focusing on national arrangements is the development and maintenance of stronger in-country technical capacities and relevant national and regional institutions and organizations. These capacities and institutions are expected to have broader benefits and applications than solely addressing REDD+ issues. High quality forest MRV systems have many obvious benefits for broader environmental monitoring, GHG accounting, sustainable economic development, and natural resource management. In addition, having such arrangements in place can enable countries to participate in future financial mechanisms, environmental markets, and/or voluntary or compliance-based regimes or mechanisms.

The objective of this chapter is to provide guidance on the key elements of national arrangements for credible and functional MRV systems for REDD+ activities. The scope of the work is limited to the MRV of GHG emissions and removals as a result of human influence on forest lands.[1] The information builds on, and complies with, requirements of the IPCC, as well as relevant elements developed in the context of the UNFCCC, and, when appropriate, the Kyoto Protocol.

This chapter discusses the following issues:

- Elements of a MRV system for REDD+;
- Key functions and components of national arrangements;
- Steps for the establishment of national arrangements; and
- Administrative and organizational arrangements, focusing on identifying stakeholders, as well as their roles and responsibilities; processes and procedures (e.g., legal and administrative arrangements).

[1] For more detailed information on the preparation of the GHG inventory, refer to Chapter 3 of this manual.

2.2 ELEMENTS OF A MRV SYSTEM FOR REDD+

2.2.1 Requirements and issues

Establishing a MRV system for REDD+ requires countries to implement a national forest monitoring system in accordance with UNFCCC Decision 2/CP.17 (UNFCCC, 2011), including various elements (see Box 2.1) and procedures. In general, countries should:

- Secure the cooperation of all stakeholders through the establishment of national arrangements;
- Have a forest inventory and a land-use change analysis (see Box 2.2);
- Be able to apply the Revised 1996 Guidelines as elaborated by the GPG-LULUCF in order to ensure the transparency, completeness, comparability, consistency and accuracy of their emissions and removals estimates;
- Have in place appropriate quality assurance/quality control (QA/QC) procedures; and
- Be able to prepare domestically verified national reports.

Box 2.1: Typical Elements to be considered by countries when determining their national context

Historical development of all REDD+ activities that are relevant for the country, including deforestation, forest degradation, conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks;

Specific geographic or other characteristics that influence the development of REDD+ activities (e.g., mountainous areas with limited or no access, potential need for regional initiatives involving neighboring countries);

Population that is affected (e.g., demographics and employment statistics related to REDD+ activities in the country);

Information related to the current and projected factors contributing to deforestation, including an analysis related to drivers of deforestation and the impact of commodities, such as soy or oil palm in the forestry sector;

Economic information related to factors that will be affected by REDD+ activities, taking into consideration various sectors of the national economy (including energy, transport, industry, mining, tourism, agriculture, fisheries, health and services);

Education, including scientific and technical research institutions focusing on issues relevant to REDD+;

Effects of past efforts to bring about land-use management and land tenure changes in the country (e.g., past investments to reduce deforestation or enhance reforestation and lessons learned);

Specific modalities for national forest MRV systems are currently under negotiation within the UNFCCC process. Some of the issues that are being considered under the UNFCCC include:

- On modalities for forest monitoring systems:
    - Developing national or sub-national (as an interim measure) systems to estimate emissions and removals;
    - Guidance by the GPG-LULUCF in order to provide data in accordance with the principles of the IPCC;
    - Strengthening forest governance, including law enforcement; consider counter-measures to deforestation and forest degradation; enhance sustainable forest management;
    - Building upon existing systems;
    - Enabling the assessment or identification of changes in natural forests;
    - Flexibility and allowing for improvements;
    - Phased-approach as mentioned in Decision 1/CP.16;
    - Identifying potential sources of uncertainties;
    - Identifying data that could help report on social and environmental safeguards; and
    - Developing a comprehensive and holistic monitoring system considering the multiple functions of forests in climate change under the joint mitigation and adaptation approach for the integral and sustainable management of forests.
- On modalities for MRV:
    - Ensuring consistency with the GPG-LULUCF;
    - Providing GHG emissions and removals data that are transparent, complete and consistent with the established reference levels (RLs);
    - Stepwise approach to improving data for relevant pools and/or gases, and to improve methodologies while recognizing financial, technical and/or technological constraints;
    - Incorporating the reporting on REDD+ in national biennial update reports (BURs) of developing countries;
    - Establishing an international consultation and analysis process (see Section 6.3.2);
    - Establishing and supporting of programs for capacity development in developing countries on all aspects of MRV; and
    - Accessing existing and future satellite imaging data.

Box 2.2: National forest inventory and land-use change analysis

A forest inventory is the systematic collection of data and forest information for assessment or analysis. An estimate of the value and possible uses of timber is an important part of the broader information required to sustain ecosystems. When undertaking a forest inventory the following items are important to measure and note: species; diameter at breast height; height; site quality; age; and defects. From the data collected one can calculate the number of trees per unit of area (e.g., hectare, acre, etc.), the basal area, the volume of trees in an area, and the value of the timber. Inventories can be performed for purposes beyond calculating the value of timber, e.g., to provide comprehensive information about the state and dynamics of forests for strategic and management planning.

A historical land-use change (LUC) analysis is the analysis of dynamics that have occurred in a given territory. The analysis assesses and quantifies the area change of specific land-use categories (e.g., forest lands, crop land, grass lands, wetlands) for a specific period of time. The information provided by the LUC analysis – together with the information provided by the forest inventory is integrated into the GHG inventory in order to estimate the associated emissions or removals from the different land-use categories and subcategories. Also, the monitoring of LUC through remote sensing is a key tool to identify and implement corrective actions in areas where illegal deforestation and degradation is occurring.

An important consideration in the MRV debate is the trade-off between the cost and accuracy of monitoring and evaluation systems for REDD+. The identification of cost-effective solutions requires a balanced approach of remote sensing and ground measurements. On one hand, imagery aids in the design of efficient ground sampling schemes, in the assessment of change areas, and in the extrapolation of plot measurements to the regional or national level. On the other hand, ground measurements are required for generating carbon data and to verify desktop forest mapping from satellite images. For more information on remote sensing, see Chapter 5 of this manual.

2.2.2 National versus sub-national accounting

One of the critical issues in the UNFCCC negotiations on REDD+ concerns the geographical scale that should be used to account for emissions. Three options have been extensively debated: the national level; the sub-national (or project) level; and both levels in a "nested approach". The different points of view expressed by different governments are the result of differing political interests and national circumstances, and because of technical issues in measuring and accounting of emissions.

The 16th session of the Conference of the Parties (COP16) encouraged developing countries to develop: i) a national REDD+ strategy; ii) national and, if appropriate, sub-national reference levels; iii) a system for MRV of GHG emissions and emission reductions; and iv) a system for providing information on how requisite social, legal, and environmental safeguards are being addressed (UNFCCC, 2010). These and other elements of REDD+ will not be implemented all at once, but rather will occur in phases. Countries can begin to implement sub-national accounting systems for REDD+ while preparing for full-scale national REDD+.

At the 17th session of the Conference of the Parties (COP17), governments agreed that if the overall performance is measured at the national level, countries could have project-level activities after the adoption of national (and potentially sub-national) reference levels (UNFCCC, 2011). The Subsidiary Body on Scientific and Technical Advice (SBSTA) is currently working on providing guidance to developing countries on establishing "national forest monitoring systems and, if appropriate, sub-national systems as part of national monitoring systems."

For countries that wish to establish both national and sub-national accounting systems, it is important to ensure that the two systems are compatible in order to safeguard the integrity of the overall accounting process. This can be achieved through:

- Identifying drivers of deforestation and forest degradation at the national and sub-national levels;
- Establishing a clear legal, regulatory and accounting framework regarding the implementation of sub-national or project activities;
- Identifying synergies between national and sub-national REDD+ activities; and
- Ensuring the consistent use of definitions of forest parameters.

For a "nested approach," it is expected that projects and/or sub-national programs would be integrated into a national level accounting. This integration can occur in stages (e.g., starting with sub-national accounting and moving up to national) or once the national accounting is in place. A national level accounting provides a complete picture of how projects, policies and measures are contributing to a country's progress in reducing emissions. It also plays an important role in helping to secure financing by projects that may be contingent on results that are measurable, reportable and verifiable.

2.3 KEY FUNCTIONS AND COMPONENTS OF NATIONAL ARRANGEMENTS[2]

In general, national arrangements for REDD+ MRV should include all institutional, legal and procedural arrangements made within a country for estimating anthropogenic emissions by sources and removals by sinks in all categories and activities included in the monitoring plan, and for reporting and archiving information. National arrangements should be designed to incorporate both general and specific functions, and be operated in such a way as to ensure:

- The transparency, consistency, comparability, completeness and accuracy of the data; and
- The quality of data through the planning, preparation and management of inventory activities.

2.3.1 General functions

General functions of national inventory arrangements include the following:

- Establishing and maintaining the institutional, legal and procedural arrangements between the government agencies and other entities involved in the preparation of emission and removal estimates from LULUCF;
- Ensuring sufficient capacity for (i) the timely data collection to estimate anthropogenic GHG emissions by sources and removals by sinks; and (ii) the technical competence of the staff involved in the inventory development process;
- Designating a single national entity with overall responsibility for the inventory; and

[2] The information on functions of national arrangements in this section is adapted from the 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 (Annex I to Decision 15/CP.17). Although Decision 15/CP.17 applies to Annex I Parties, the provisions contained within it on national arrangements would be generally applicable to all countries.

- Preparing GHG inventories in accordance with any relevant reporting guidelines.

2.3.2 Specific functions

Specific functions of national inventory arrangements include collecting activity data (AD), selecting appropriate methods and emission factors (EFs), estimating anthropogenic GHG emissions by sources and removals by sinks, implementing uncertainty assessments and QA/QC activities, and carrying out procedures for the verification of the data.

2.3.3 Implementation phases

Implementation of national arrangements for REDD+ MRV involves three phases: inventory planning, inventory preparation, and inventory management.

2.3.4 Inventory planning

Inventory planning includes activities that lead up to the implementation of the MRV activities. As part of its inventory planning, a country will:

- Define and allocate specific responsibilities in the inventory development process, including the roles of, and the cooperation between, government agencies and other entities involved in the preparation of the inventory, as well as the institutional, legal and procedural arrangements made to prepare the inventory;
- Elaborate an inventory QA/QC plan;
- Establish processes for the official consideration and approval of the inventory, including any recalculations;
- Consider ways to improve the quality of AD, EFs, methods and other relevant technical elements of the inventory once they have been initially established. Information obtained from the implementation of the QA/QC programme, and other verification activities should be considered in the development and/or revision of the QA/QC plan and the quality objectives;
- Ensure there is sufficient capacity to carry out all activities through training of existing personnel or hiring of experts; and
- On the basis of any periodic evaluations of the inventory preparation process, re-evaluate the inventory planning process.

2.3.5 Inventory preparation

Inventory preparation includes all aspects of implementation of the MRV actions, as well as their organization into a reporting format. As part of its inventory preparation, a country would:

- Collect sufficient AD, process information and EFs as necessary to support the methods selected for estimating anthropogenic GHG emissions and removals;
- Prepare estimates of GHG emissions and removals in accordance with the requirements defined by the UNFCCC;
- Make quantitative estimates of uncertainty;

- Implement general inventory QC procedures in accordance with its QA/QC plan, following the guidance provided by the IPCC;
- Apply category-specific QC procedures for key categories (see Box 2.3) and for those individual categories in which significant methodological and/or data revisions have occurred, in accordance with the guidance provided by the IPCC;
- Provide for a basic review of the inventory by personnel that have not been involved in the inventory development process, preferably an independent third party, before the submission of the inventory, in accordance with the planned QA procedures; and
- Following the basic review mentioned above, provide for an extensive expert review of key categories, as well as for categories where significant changes to methods or data have been made, in accordance with the guidance provided by the IPCC.

Box 2.3: Key categories

Key categories refer to specific elements within a GHG inventory, which are important, in terms of their contribution, to the total emissions/removals, or to the total uncertainty, or to the trends of emissions/removals for the years covered by the inventory. They represent a central element of the IPPC Guidelines, helping to identify the most appropriate methodologies for specific activities. Methodological choice for individual source and sink categories is important in managing overall inventory uncertainty. Generally, inventory uncertainty is lower when emissions and removals are estimated using the most rigorous methods provided for each category or subcategory in the sectoral volumes of these Guidelines. However, these methods generally require more extensive resources for data collection, so it may not be feasible to use more rigorous methods for every category of emissions and removals. It is therefore good practice to identify those categories that have the greatest contribution to overall inventory uncertainty in order to make the most efficient use of available resources. By identifying these key categories in the national inventory, inventory compilers can prioritize their efforts and improve their overall estimates. It is good practice for each country to identify its national key categories in a systematic and objective manner. Consequently, it is good practice to use results of a key category analysis as a basis for methodological choice. Such a process will lead to improved inventory quality, as well as greater confidence in the estimates that are developed.

According to the IPCC, a key category is one that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of GHGs in terms of the absolute level, the trend, or the uncertainty in emissions and removals. Whenever the term key category is used, it includes both source and sink categories as well as specific GHGs. In terms of absolute level, key categories are all inventory activities that account for 95 percent of the total GHG emissions.

For more information, see section 5.4 of the IPCC GPG-LULUCF (IPCC, 2003).

2.3.6 Inventory management

Inventory management refers to the handling of the inventory report and its relevant source information once an inventory cycle is complete. As part of its inventory management, a country would archive all relevant inventory information for the reported time series, including:

- All disaggregated EFs and AD together with explanations of the rationale for selecting these factors and data, as well as how they have been generated and aggregated for the preparation of the inventory;
- A description of the methods used for the identification of key category identification;
- Explanation of how QA/QC procedures have been implemented; and
- Findings of external and internal reviews and descriptions of planned inventory improvements as a result of these reviews.

Another part of inventory management is ensuring that the country has the capacity to respond in a timely manner to requests for clarifying information on the national inventory. Many countries have well-established systems for the collection and processing of non-GHG related information. Such systems involve database management processes for archiving data and information. Experience in the use of such systems would be extremely valuable for application to GHG inventory development and/or strengthening of procedures to archive, store, and retrieve information. Countries should look at their experience in other areas for guidance and resources on this issue. The length of the inventory cycle depends on national circumstances and reporting requirements. An example of an inventory cycle is shown in the diagram in Figure 2.1. Such a cycle can be applied to annual, biennial, or longer-term periods.[3]

Figure 2.1 A typical cycle for an inventory process (source: EPA National System Template). For more information, see section 2.7 of this manual.

[3] It should be noted that national forest inventory data would not be available annually, but every few years (typically between three to ten years).

2.4 STEPS IN ESTABLISHING INSTITUTIONAL ARRANGEMENTS

Establishing institutional arrangements includes a number of specific activities, which depend on the MRV goals that have been identified by a country, including, but not limited to, preparation of national reports and communications to meet international commitments, seeking funding for REDD+ projects, implementation of national or regional initiatives on REDD+.

The first step in the process to establish national arrangements is to identify specific actions consistent with MRV goals and develop a plan for their completion, including securing the resources and commitment of all relevant stakeholders in the country. This may include setting up working groups and task forces to undertake specific tasks, as well as establishing specific procedures and systems, such as for the collection and archiving of information. To ensure timely completion, it is necessary to identify existing national capacities and allocate necessary funds, as well as human and other resources.

Once the specific actions are identified, a country would need to implement the necessary administrative and organizational arrangements. Every country will likely have its own approach on how to put in place these arrangements for REDD+. Some typical approaches include:

- Completely out-sourcing the inventory preparation process to an outside organization, such as a consulting company, a university, or a research institute;
- A small team of government employees overseeing the preparation of the inventory by a number of consultants and researchers;
- Forming an advisory or oversight board composed of representatives from multiple agencies and ministries, and possibly other organizations such as non-governmental organizations (NGOs), academia, or others in the private sector, that make decisions and oversee the inventory preparation process;
- Preparation of the inventory almost entirely by government employees within a single agency; and
- Preparation of the inventory delegated to the country's provinces or states. The separate provincial inventory information is then aggregated at the national level.

Many other situations, including combinations of the above, are possible and there is no absolutely correct approach. Each approach is associated with relative pros and cons and has financial and staffing implications. Whatever approach is used, it should function in such a way that the quality of the inventory is maintained and improved over time and that decisions can be made in an effective and timely manner.

Whatever approach is taken, in terms of administrative and organizational arrangements, the process necessitates developing clear roles and responsibilities. The national-level lead agency or institute should be charged with the overall responsibility, possibly mandated by national legislation, to deal with a REDD+ MRV system, perhaps as a subset of a more comprehensive GHG inventory. It is important that:

- The appropriate body be identified at an early stage of the process, as it will make it easier for the personnel to be appointed and for specific roles and responsibilities to be allocated; and
- The appointment is made clear to all stakeholders in the process so that there is no ambiguity of which institution leads the process.
- In general terms, this institutional body will be required to manage the work of the other institutions and organizations and will have the overall responsibility for the coordination of administrative and technical arrangements, and the overall quality of reported estimates.

- The management system that a country uses will be determined by national circumstances. Some common patterns include:

- Centralized vs. decentralized: The country's lead agency may maintain a large degree of control and decision-making authority over the inventory preparation process. A centralized approach will likely include few other institutions. A decentralized approach, in contrast, may include many different teams and/or institutions that each work on different parts of the inventory and make their own decisions regarding methodologies and other issues. Countries with a large administration and various institutions with expertise in certain areas of the inventory often use the centralized approach. In such cases, the lead agency usually has more of a coordinating role and less power over decisions on methodological issues.

- In-sourced vs. out-sourced: Government agencies and employees may prepare most, or all, of the inventory, thus "in-sourcing" the process. Alternatively, the government may "out-source" the work of preparing the inventory to private consultants, research institutions, academic institutions, or other NGOs, for example. The decision on out-sourcing depends on whether the administration has developed sufficient capacity and capability to do all or most of the technical work itself through the involvement of experts and agencies. Often smaller countries resort to extensive use of external assistance due to lack of expertise and the length of time necessary to build capacity within the specific timeframe for the preparation of a GHG inventory.

- Single agency vs. multi-agency: The lead agency may be housed within a single government agency, or the country's lead body may be composed of a multi-agency working group, committee, or other structure. Such a multi-agency structure requires a very clear delineation of roles and responsibilities to ensure that there is a clear line of reporting and decision-making on GHG inventory issues. Although the multi-agency approach may have some relative advantages in regard to plurality in the decision-making process, in practice one agency will often have the overall coordinating role to avoid conflicts.

- Integrated vs. separate: The country's GHG inventory work may be integrated with other related efforts (e.g., reducing threats to biodiversity, water management, avoiding soil erosion) to ensure the best use of resources and utilize available expertise.

While developing a MRV system for REDD+ activities, a country has the opportunity to identify those national and regional development priorities and objectives that would serve as the basis for addressing REDD+ and climate change. Such information would provide the background to help a country understand better, inter alia, its own specific conditions, existing national capacities and available options for addressing GHG emissions and removals from REDD+ within the broader context of sustainable development.

At every step of the process it is imperative that countries keep track of the specific roles and responsibilities of all relevant organizations, as well as changes in the arrangements as refinements and/or new stakeholders are involved. One way to do this in a systematic way is through the use of the National System Templates from the United States Environmental Protection Agency (EPA). Although these templates have been developed to address the national arrangements of a national GHG inventory covering all economic sectors, it is possible to modify them for the purposes of a GHG inventory on LULUCF. A brief description of the templates and an example of how they could be modified are provided in Appendix 2.

2.5 EXAMPLES

In this section we present examples of institutional arrangements for Brazil, Colombia, and India for the preparation of GHG inventories for the LULUCF sector. The information in this section is based on the World Resources Institute (WRI) Measurement and Performance Tracking Project National GHG Inventory Case Study Series.[4]

2.5.1 Brazil

The Foundation of Space Science, Applications and Technology (FUNCATE) was the sole institution in charge of compiling the Brazilian LULUCF inventory, in coordination with the General Coordination on Global Climate Change under the Brazilian Ministry of Science, Technology and Innovation (MCT). FUNCATE had a clear mandate established through a contract or cooperation agreement that set individual terms of reference, timetable, costs, and responsibilities. FUNCATE engaged other agencies, associations, and academic and research institutions, but did not subcontract any components of the LULUCF inventory.

Forty-five personnel were engaged in the work at different stages of the inventory development (22 image interpreters, one general coordinator, seven administrators, five validation and data analysis staff, one information technology expert, three system development staff, three auditors, one database development expert, one database management expert, and one documentation specialist). The experience gained from the first national inventory and the new demands from application of the GPG-LULUCF helped to identify the initial level of human resources needed. However, as the work progressed, FUNCATE identified the need to enlarge the team, which varied in size according to the stage of development of the project. For instance, a large number of image interpreters were needed at the beginning of the project but were latter allocated to other work within FUNCATE or dismissed. The number of personnel engaged was driven by the product delivery time schedule and budget. With each new staff hire by FUNCATE, training was carried out to ensure consistency in image classification among the different image interpreters and thus minimize classification uncertainty.

Inventory coordination at FUNCATE was carried out by one person with experience in remote sensing whose role was to oversee the development of the inventory at all phases (including the compilation of the GHG data for the LULUCF inventory), ensure that the budget expenditure and the agreed timetable evolved according to the contract and cooperation agreement with MCT, perform additional QC procedures, and prepare the partial and final reports. This person had overall knowledge of the inventory's development and actively participated at all phases.

No external people were engaged directly in the preparation of the inventory, besides those from FUNCATE, MCT, and Brazil's National Space Research Institute (INPE). During development of the activities for the project (e.g., image classification), personnel involved worked full-time until completion of that activity. Other people, such as those involved in system development, worked simultaneously for other projects at FUNCATE. Most of the staff was engaged full time in the project.

The LULUCF inventory was the most expensive among all sectors reported in the national GHG inventory. The second inventory, in particular, had an added cost due to the new methodological requirements from using the GPG-LULUCF. Part of this added cost was caused by the decision to create a spatially explicit database and the wall-to-wall character of the territorial coverage required to include other land-use categories

[4] Full reports are available at: https://sites.google.com/site/maptpartnerresearch/national-ghg-inventory-case-study-series/producing-a-national-ghg-inventory-for-the-land-use-land-use-change-and-forestry-lulucf-sector.

previously not considered (e.g., selective logging). The idea was to create a database that would facilitate the updating and recalculation of previous inventory estimates, if necessary. This required national wall-to-wall coverage with remotely sensed data of adequate resolution. The total cost of the second national inventory was approximately 1.1 million distributed among a cooperation agreement and a contract. The cost included salaries and labor benefits, equipment, consumables, travel expenses, database construction, and part of the development of a software tool to manage large datasets. The budget did not contemplate the acquisition of data other than those planned under the legal instruments. All costs for each phase of the project were detailed by FUNCATE and helped MCT to prioritize the activities, eliminate those considered not relevant for the final product, and agree on the final allocation of the full budget for LULUCF.

Major funding came from the Global Environment Facility (GEF) and from MCT. A small portion of the budget was ensured by the Ministry of the Environment. No consultants were hired for the project.

2.5.2 Colombia

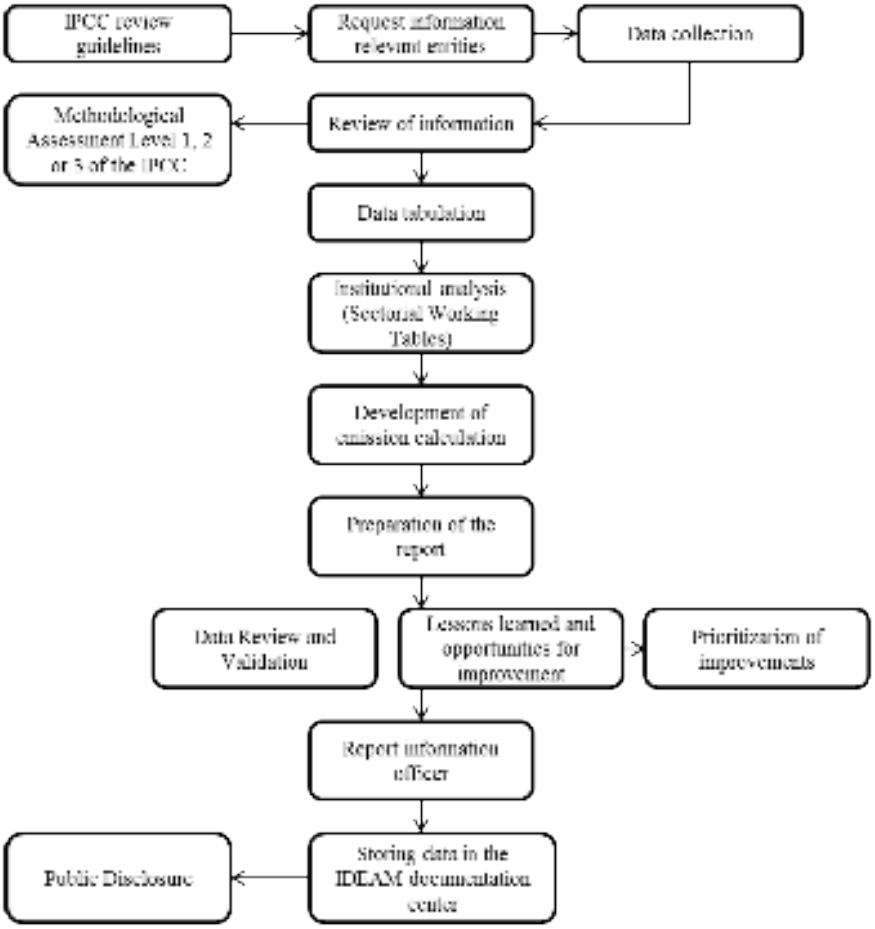
Colombia has prepared two national communications under the UNFCCC. Although the working method to prepare these communications has been effective, the process, familiarization of guidelines, and acquisition of data starts from scratch for each new GHG inventory, as there is no centralized technical platform to share and exchange information with other LULUCF-related institutions in a permanent, timely, and efficient manner. The only national system in place, the National Environmental System (SINA), comprises a set of overarching principles that focus on environmental principles to foster management of the country's natural resources. The lack of a system to share data also prevents the implementation of comprehensive QC procedures nationwide. One option being considered is for both the national and regional institutions responsible for the collection, compilation, analysis, and systematization of forestry information to develop the revision mechanisms controlling the flow of information; this should improve the quality, frequency, and availability of the reported data. It would also be necessary to identify priority data at the national, regional, and local level that are needed as a basic input for research and to comply with international commitments. Below we provide some more details regarding the overall system in place.

The institute responsible for conducting the GHG inventory is the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM); a public institution that is part of the Ministry of Environment and Sustainable Development (MADS). IDEAM is responsible for selecting public and private institutions that are actively participating in the inventory-related sectors (e.g., energy, transportation, waste, industry, agriculture, and LULUCF) to form sectoral working groups. The working groups' ultimate objectives are to define needs and priorities for each sector and to select EFs and methods for calculating the uncertainty associated with each module.

IDEAM also provides technical and scientific support to the agencies that constitute SINA. SINA is a set of norms, regulations, activities, resources, programs, and institutions that fosters compliance with the environmental principles embedded in the constitution. SINA comprises several institutions at the local, regional, and national level that collectively generate information, carry out scientific research, and build technological capacities for their own purposes. However, SINA does not have any technical platform to share information online. Therefore, each one of the institutions involved compiles and archives the data on its own portal site.

The institutional arrangements are based on voluntary agreements among the following organizations: MADS, the Ministry of Agriculture and Rural Development, the National Corporation for Forestry Research and Development, the Association of Regional Autonomous Corporations and Sustainable Development, Regional Autonomous Corporations, universities, private entities (e.g., Pizano S. A., Carton de Colombia, etc.), the Amazon Institute for Scientific Research, the Geographic Institute Agustin Codazzi, Bogota's Botanical Garden Jose Celestino Mutis, the Environmental Research Institute of the Pacific, the Special Administrative Unit of the National Parks System, and the Integrated Monitoring System for Illicit Crops. Currently, the development of the GHG inventory encompasses the steps illustrated in Figure 2.2.

Figure 2.2: Key steps for national inventory preparation in Colombia

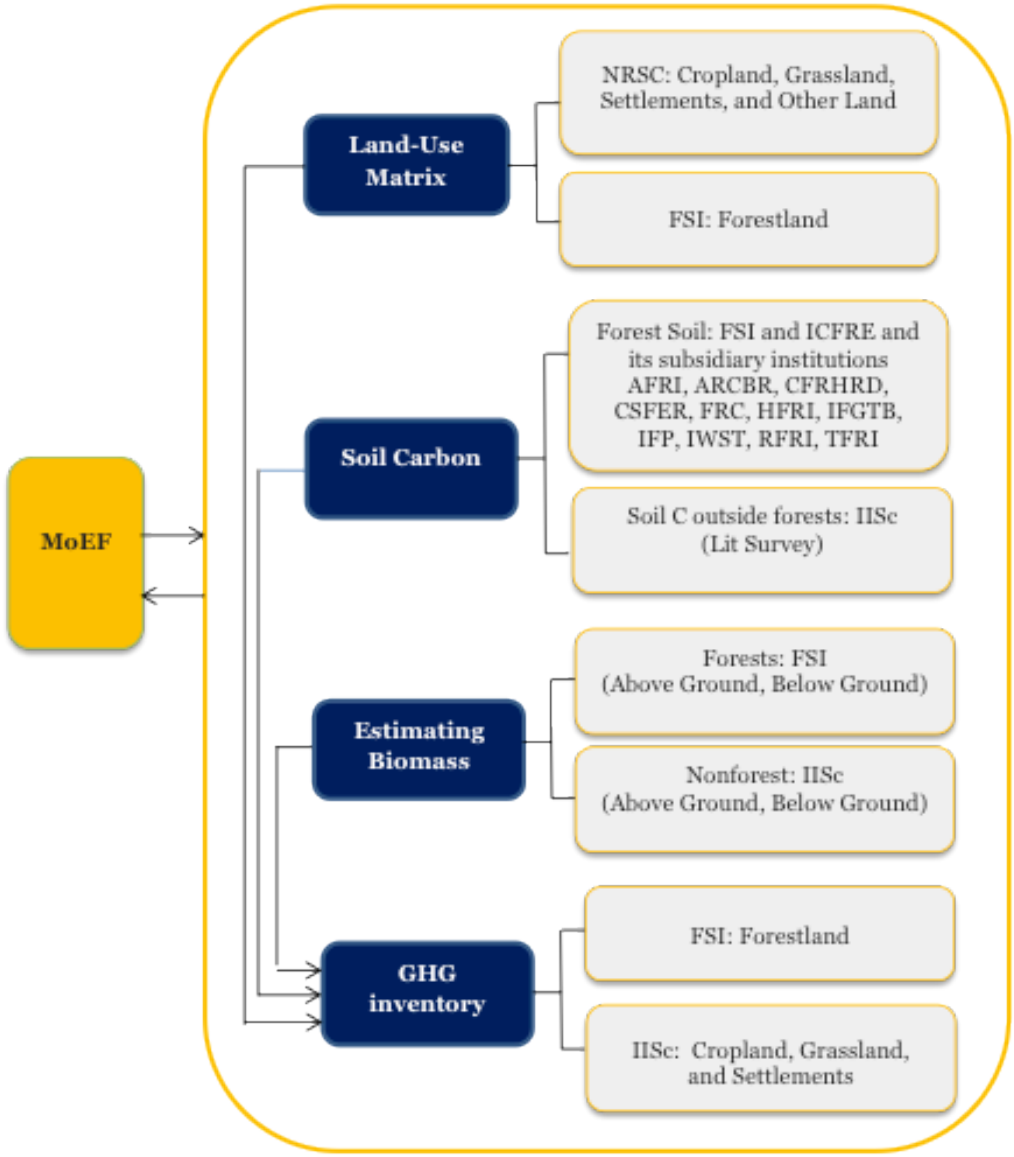


2.5.3 India

India's overall arrangement structure for the preparation of GHG estimation for the LULUCF sector is shown in Figure 2.3. The Ministry of Environment and Forests is responsible for the overall coordination of the process. Various other institutions involved in the LULUCF sector provide technical assistance and expertise to ensure that all methodological processes are followed in order to develop a comprehensive and accurate inventory to the extent that capacities permit.

The coordination process has evolved over the years. Initially, the Indian Institute of Science took a leading role as it was the institution involved in the IPCC process for developing the GHG emissions inventory for the LULUCF sector. The current approach involves cooperation with other organizations, such as the Forest Survey of India (FSI), the National Remote Sensing Centre, and the Indian Council of Forestry Research and Education, which meet on a regular basis to both decide on the respective roles and establishment of these roles, as well as to ensure that all activities are implemented in a timely fashion.

Figure 2.3: Work allocation and implementation arrangements for developing the GHG emissions inventory by sources and removal by sinks for the LULUCF sector in India



Here IFGTB: Institute of Forest Genetics and Tree Breeding, Coimbatore; IWST: Institute of Wood Science and Technology, Bangalore; TFRI: Tropical Forest Research Institute, Jabalpur; RFRI: Rain Forest Research Institute, Jorhat; AFRI: Arid Forest Research Institute, Jodhpur; HFRI: Himalayan Forest Research Institute, Shimla; IFP: Institute of Forest Productivity, Ranchi; CSFER: Centre for Social Forestry and Eco-Rehabilitation, Allahabad; CFRHRD: Centre for Forestry: Research and Human Resource Development, Chhindwar; FRC: Forest Research Centre, Hyderabad; ARCBR: Advanced Research Centre for Bamboo and Rattans, Aizawl, IISc: Indian Institute of Science; FSI: Forest Survey of India; NRSC: National remote Sensing Centre.

Funding for all activities is part of the Indian Geosphere Biosphere Programme of the Indian Space Research Organisation. For example, the Natural Resource Management Division, which covers land-use mapping, has been granted a budget of 537.4 million Rupees (or $9.95 million) for 2012-13 (Union Budget, 2012-13), compared to the 68.75 million Rupees (or $1.27 million) that was allocated in the budget for preparation of the entire GHG emissions inventory for the second national communication, spread over four years.

Similarly, preparing the GHG emissions inventory is part of the FSI mandate and has been funded through the forestry and wildlife budget of the Ministry of Environment and Forest, the parent organization of FSI. The budget outlay of its Forestry and Wildlife Division is 9,066.8 million Rupees (or $167 million) for 2012-2013 (Union Budget 2012-13). The Indian Institute of Science (IISc) was also funded through the second national communication, and several other sources, including governmental, bilateral, and multilateral funds.

2.6 REFERENCES

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2.7 EPA NATIONAL SYSTEM TEMPLATES

EPA's National System Templates can be used as a set of building blocks by countries to construct a national inventory management system (see http://www.epa.gov/climatechange/emissions/ghginventorycapacitybuilding/templates.html for more details and for how to download the templates). The advantages of the templates are that they:

- Focus on documenting essential information in a concise format and avoid unnecessarily long written reports;
- Standardize tasks, allowing countries within regions to compare and contrast results;
- Ensure roles and responsibilities are understood;
- Accommodate varying levels of national capacity;
- Provide an objective and efficient system for identifying priorities for future improvements;
- Serve as instruction manuals and a starting point for future inventory teams; and

- Create transparency in a country's national system and improve quality over time.

The six templates (briefly described below) can be compiled into a single National Inventory System Report, typically less than 50 pages, providing comprehensive documentation of each of the critical national system building blocks. The Key Category Analysis (KCA) Tool can be used to determine key categories in a GHG inventory.

Template 1: Institutional Arrangements for National Inventory System

This template assists inventory teams in assessing and documenting the strengths and weaknesses of existing institutional arrangements for inventory development. This ensures continuity and integrity of the inventory, promotes institutionalization of the inventory process, and facilitates prioritization of future improvements.

Template 2: Methods and Data Documentation

This assists inventory teams in documenting and reporting the origin of methodologies, activity datasets, and EFs used to estimate emissions or removals. Future inventory teams can refer to the completed template for each source and sink category to determine what information was collected, how the data was obtained, and what methods were used.

Template 3: Description of QA/QC Procedures

This guides countries through the establishment of a cost-effective QA/QC program to improve transparency, consistency, comparability, completeness, and confidence in national GHG inventories. Supplemental checklists with recommended QA/QC procedures have been developed for the Inventory Coordinator and QA/QC Coordinator.

Template 4: Description of Archiving System

An archive system is an inexpensive yet critical step in the sustainability of the National Inventory System. An archive system allows estimates to be easily reproduced, safeguards against data and information loss, and allows reproducibility of the estimates.

Template 5: Key Category Analysis (KCA)

KCA provides information, according to IPCC criteria, on which sources or sinks are the most important and should be the focus of improvement efforts. The KCA Tool enables a country to determine key categories from a GHG inventory.

Template 6: National Inventory Improvement Plan

Synthesizes findings and describes specific priorities for future capacity building projects based on the needs identified in the first five templates and facilitates continual inventory improvements.

Example of modifying Template 1 for the purposes of a LULUCF GHG inventory

Step 1:

List the lead agency and describe the arrangements or relationship between the LULUCF Inventory Agency/Organization and the UNFCCC Focal Point Agency, if different (Table 2.1).

Step 2:

List additional information, specific to the contacts/experts for inventory development, for the LULUCF sector (Table 2.3). One table is provided for the LULUCF sector to document existing arrangements for obtaining, compiling and reviewing inventory data. Identify the role, organization, and contact information for those providing relevant data for estimating emissions. Example roles are provided in the table below.

Step 3:

Within the LULUCF sector list, identify where well-established institutional arrangements needed to prepare the inventory exist, where data have been collected and managed adequately and, thus, where strengthening is not needed (Table 2.3). Given the key category analysis and existing institutional arrangements within each sector, identify what improvements are needed to enhance the institutional arrangements for each sector and list these in Table 2.4. In preparing this section, consider whether any important tasks for inventory preparation have not been assigned or delegated, and determine whether they could be assigned.

In the "Comments" section of this table, provide information on the status of the institutional arrangement or any additional information not included within the table. Explain in detail how the arrangements were established. For example, the data provider listed in the Table provides the statistics that will be used in the inventory. Describe the strategies that were used to collect the necessary inventory data from an organization. In this description, address the following questions and add additional comments as necessary:

- Is there a formal legal contract between the organizations?
- Was there a meeting with the experts, data providers, and other key contributors explaining the background and purpose of the inventory?
- Is it an informal arrangement (e.g., written or verbal communication with staff)?
- How was the request for data made?
- At what level of management was the request made?
- How was the organization motivated to share its data and information with the inventory agency?

Table 2.1: Designated inventory agency; identifies the inventory management team members. The status of the institutional arrangements can be noted in the "Comments" column

Designated National LULUCF GHG Inventory Preparation Agency/Organization	UNFCCC Focal Point (Name) and UNFCCC Focal Point Agency	Describe the arrangements or relationship between LULUCF Inventory Agency/Organization and UNFCCC Focal Point Agency, if different.

Table 2.2: National inventory management team

Role	Name	Organization	Contact Information	Comments
Inventory Director/Coordinator				
LULUCF Sector Lead				
Archive (Data and Document) Manager/Coordinator				
QA/QC coordinator				
Uncertainty Analysis coordinator				
Other: e.g., GHG Policy Specialist who tracks capacity building efforts and IPCC processes				

Table 2.3: LULUCF sector institutional arrangements

Role	Name	Organization	Contact Information	Comments
Inventory Director/Coordinator				
LULUCF Sector Lead				
Archive (Data and Document) Manager/Coordinator				
QA/QC coordinator				
Uncertainty Analysis coordinator				
Other: e.g., GHG Policy Specialist who tracks capacity building efforts and IPCC processes				

Table 2.4: Potential improvements in management structure of the national inventory system

Sector/REDD+ activity	Strengths in Management Structure of the LULUCF National Inventory System	Potential Improvements in Management Structure of the LULUCF National Inventory System	Comments
LULUCF (general)			
Deforestation			
Forest degradation			
Conservation of forest carbon stocks			
Sustainable management of forests			
Enhancement of forest carbon stocks			

3.0 ESTIMATING GREENHOUSE GAS EMISSIONS AND REMOVALS

Authors: Angel Parra and Stelios Pesmajoglou

3.1 INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC) Guidelines, the fundamental basis for the Greenhouse Gas (GHG) inventory methodology for land use and land-use change in forests, including REDD+, rests upon two linked assumptions:

- The flux of carbon dioxide (CO2) to/from the atmosphere is equal to changes in carbon stocks in the existing biomass and soils; and
- Changes in carbon stocks can be estimated by first establishing the rates of change in land use, the practice used to convert the land to a different use (i.e., burning, clear-cutting, selective cutting, change in silviculture or management practice, etc.), and the carbon stocks before and after the change. This requires estimating:
    - The land use in the inventory year;
    - The conversion of forest to a different land use; and
    - The stocks of carbon in the land-use categories (both those that are subjected to change and those that are not).

To estimate GHG emissions and removals, it is important to consider: the inventory scope; estimation methodologies; and data needs.

In the context of reducing emissions from deforestation and forest degradation (REDD+), a national GHG inventory should cover all anthropogenic emissions and removals within the national boundaries and over a specific time period (i.e., a calendar year or a multi-year time period). Anthropogenic emissions and removals are defined as those occurring on managed lands.[5] The term managed lands is defined fairly broadly and although it is not strictly the same as anthropogenic activities it is most commonly used as the best approximation available on a global basis.

[5] Countries can use their own definitions of managed and unmanaged lands, which may refer to internationally accepted definitions, such as those by FAO, Ramsar, etc. For that reason no definitions are given here beyond broad descriptions. Managed land may be distinguished from land that is unmanaged by fulfilling not only the production but also ecological and social functions. The detailed definitions and the national approach to distinguishing between unmanaged and managed land should be described in a transparent manner in the inventory report (IPCC GPG 2003), available at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp2/Chp2_Land_Areas.pdf.

The minimum requirement for a country to participate in a mitigation mechanism connected to a financial process (e.g., REDD+) is to have the capacity and capability to compile a GHG inventory with estimates of carbon stock changes with a known uncertainty. For the purposes of this manual, the estimation methodologies described are those from the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forests (GPG-LULUCF), which are consistent with those in the 2006 IPCC Guidelines (IPCC, 2003). To meet this condition, a country needs to have: 1) country-specific estimates of emissions factors (EFs) by using, for example a National Forest Inventory, for those changes associated with forest lands; 2) multi-temporal inventory data; and 3) uncertainty estimates associated with any data reported.

This chapter provides a brief description of the GPG-LULUCF and discusses the following:

- A brief overview of IPCC guidance evolution;
- The main steps for estimating emissions and removals for REDD+ activities;
- Main carbon pools;
- Land-use types;
- Methodologies for estimating emissions and removals;
- Activity data (AD); and
- Emission factors.

More detailed and technical information on the collection of data for input onto GHG estimation is provided in Chapters 4 and 5.

3.2 IPCC GUIDANCE

3.2.1 The Good Practice Guidance for Land Use, Land-Use Change and Forestry

As discussed in section 7.1, the IPCC developed GPG-LULUCF in 2003 (IPCC, 2003) as a supplement to the Revised 1996 IPCC Guidelines (IPCC, 1996). Its main objectives are:

- To assist countries in producing national GHG inventories for the LULUCF sector that are transparent, consistent, complete, comparable and accurate; and
- To provide good practice guidance on the choice of estimation methodology and improvements of the methods, as well as advice on cross-cutting issues, including estimation of uncertainties, time series consistency, quality assurance, and quality control.

The GPG-LULUCF provides guidance on specific features related to the LULUCF sector including:

- Consistent representation of land areas;
- Sampling for area estimates and for estimating emissions and removals;
- Verification; and
- Guidance on how to complement the Convention reporting for the LULUCF sector to meet the supplementary requirements under the Kyoto Protocol.

Other advances of the GPG-LULUCF are the inclusion of:

- A key source/sink category analysis, enabling the dedication of limited inventory resources to important source/sink categories, CO2 pools, and non-CO2 gases;
- All five carbon pools (aboveground biomass, belowground biomass, deadwood, litter, and soil organic carbon);
- CO2 emissions and removals estimates for all carbon pools; and
- The following non-CO2 gas estimates:
    - Nitrogen dioxide (N2O) and methane (CH4) from forest fires;
    - N2O and CH4 from managed wetland;
    - N2O from managed (fertilized forests);
    - N2O from drainage of forest soils; and
    - N2O from land-use conversion.

Inventories can be organized according to six broad land-use categories: forest land; cropland; grassland; wetlands; settlements; and other land. These land-use categories can be further sub-divided into lands remaining in the same land use, e.g., Forest Land Remaining Forest Land, during the period covered by the inventory, and lands converted into another land-use category, e.g., Forest Land Converted to Cropland, during the inventory period.

Table 3.1 summarizes the differences between the Revised 1996 Guidelines, the GPG-LULUCF 2003, and the 2006 IPCC Agriculture, Forestry, and Other Land Use (AFOLU) Guidelines.

3.2.2 2006 IPCC Guidelines

The 2006 IPCC Guidelines on National Greenhouse Gas Inventories represent an evolutionary development in the methodologies for GHG inventories (IPCC, 2006). The most significant change introduced was the consolidation of the LULUCF sector and the Agriculture sector into a single sector referred to as Agriculture, Forestry and Other Land Use (AFOLU).

Other changes for the AFOLU sector include:

- Adopting the six land-use categories used in GPG-LULUCF (forest Land, cropland, grassland, wetlands, settlements, and other land). These land categories are further sub-divided into land remaining in the same category and land converted from one category to another. The land-use categories are designed to enable inclusion of all managed land area within a country;
- Reporting on all emissions by sources and removals by sinks from managed lands, which are considered to be anthropogenic, while emissions and removals for unmanaged lands are not reported;
- Generic methods for accounting of biomass, dead organic matter and soil carbon stock changes in all land-use categories and generic methods for GHG emissions from biomass burning that can be applied in all land-use categories;
- Incorporating methods for non-CO2 emissions from managed soils and biomass burning, and livestock population characterization and manure management systems from agriculture;

Adopting three hierarchical tiers of methods that range from default emission factors and simple equations to the use of country-specific data and models to accommodate national circumstances;

- Describing alternative methods to estimate and report carbon stock changes associated with harvested wood products;
- Incorporating key category analysis (KCA) for land-use categories, carbon pools, CO2 and non-CO2 GHG emissions;
- Adhering to principles of mass balance in computing carbon stock changes;
- Greater consistency in land area classification for selecting appropriate emission and stock change factors and AD;
- Improving default emissions and stock change factors, as well as development of the IPCC Emission Factor Database (EFDB) that is a supplementary tool to the 2006 IPCC Guidelines, providing alternative emission factors with associated documentation; and
- Incorporating methods to estimate CO2 emissions from flooded land with methods for CH4 emissions contained in an appendix, reflecting the limited availability of scientific information.

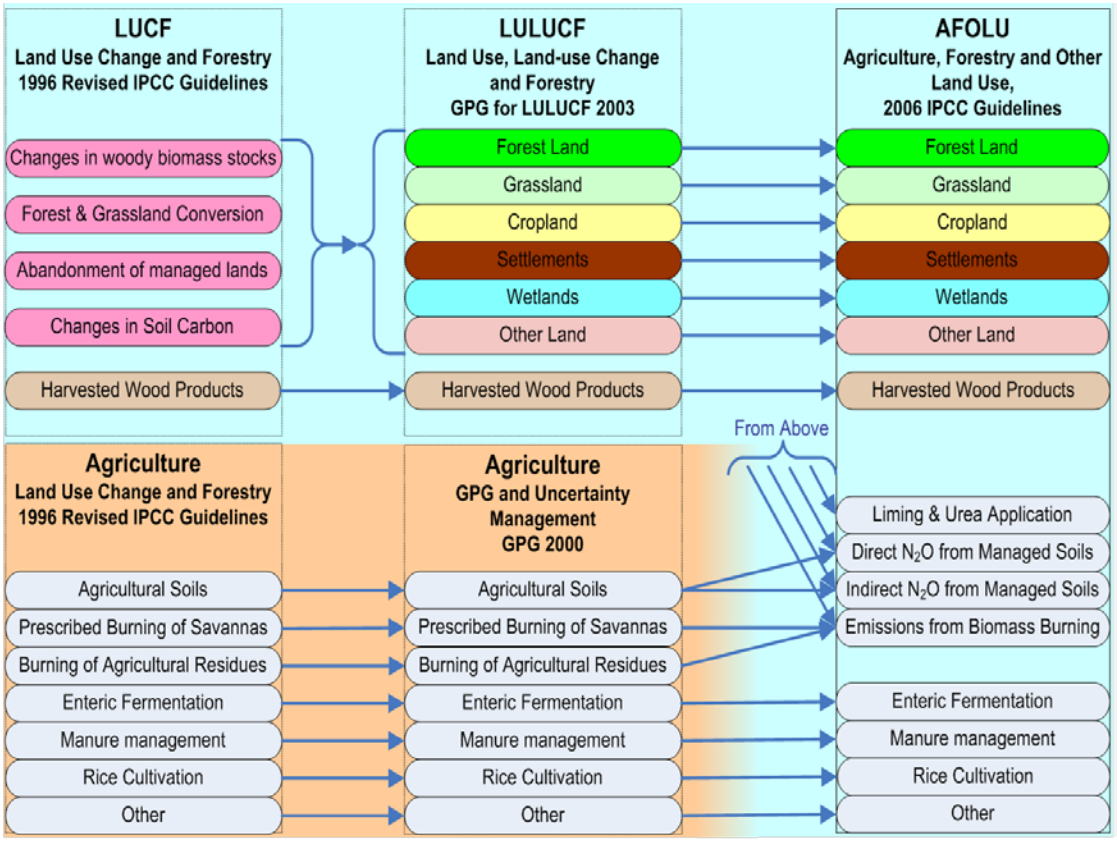
Table 3.1: Differences between 1996 Guidelines, 2003 GPG-LULUCF and 2006 AFOLU

Revised 1996 IPCC Guidelines	2003 GPG-LULUCF	2006 IPCC Guidelines AFOLU Sector
Approach for reporting based on four categories: ➢ Changes in forest and other woody biomass stocks ➢ Forest and grassland conversion ➢ Abandonment of croplands, pastures, or other *managed* lands ➢ CO_2 emissions and removals from soils Some land categories not included, such as coffee, tea, coconut. Lack of clarity on agroforestry.	Approach for reporting based on six land categories: ➢ Forest land ➢ Cropland ➢ Grassland ➢ Wetlands ➢ Settlements ➢ Other land	Agricultural sector is merged with LULUCF in order to ensure consistency and avoid double counting. The reporting for land categories remains similar to the GPG 2003.
Forests and Grassland categories subdivided according to the four reporting categories: ➢ Changes in management	The six land categories are further subdivided into: ➢ Land remaining in the same use category	Similar

➢ Conversion ➢ Abandonment ➢ Cultivation	➢ Land converted into another use category	
Methods provided mainly for aboveground biomass and soil organic carbon. Default assumption: changes in dead organic matter and belowground biomass are zero (i.e., inputs equal losses).	Methods given for measurement and estimation of all five carbon pools: ➢ Aboveground biomass ➢ Belowground biomass ➢ Dead organic matter ➢ Litter ➢ Soil organic carbon Methods given for all non-CO_2 gases.	Incorporation of methods for non-CO_2 emissions from *managed* lands, soils and biomass burning, and livestock population characterization and manure management systems from agriculture. Incorporation of methods to estimate CO_2 emissions from flooded land with methods for CH_4 emissions contained in an appendix, reflecting the limited availability of scientific information. Description of alternative methods to estimate and report carbon stock changes associated with harvested wood products.
Key source/sink category analysis not provided.	Key source/sink category analysis provided for the selection of: ➢ Land categories ➢ Land sub-categories ➢ Carbon pools ➢ CO_2 and non-CO_2 gases	Similar
Key AD required: ➢ Area of plantations/forest ➢ Forest area converted ➢ Average area converted (10-year average) ➢ Area abandoned and regenerating to forest: 20 years before year-t (year of the	Key AD required: ➢ Area of forest land remaining forest land and area of other land category converted into forest land, disaggregated by: climatic region, vegetation type, species, management system, etc. ➢ Forest area affected by disturbances	Similar

inventory) and 20-100 years before year-t ➢ Area under different land use/management systems and soil type: during year-t and 20 years before year-t ➢ Area under managed organic soils	➢ Forest area affected by fire ➢ Land afforested derived from cropland/grassland ➢ Land converted to forest through plantation or natural regeneration	
Key Emission Factors required: ➢ Annual biomass transferred into deadwood ➢ Annual biomass transferred out of deadwood ➢ Litter stock under different management systems ➢ Soil organic carbon in different management systems ➢ Amount of biomass fuel present in an area subjected to burning	Key Emission Factors required: ➢ Average annual net increment in volume suitable for industrial processing. ➢ Biomass Expansion Factor (BEF) for conversion of annual net increment (including bark) to aboveground tree biomass increment ➢ Root: shoot ratio appropriate to increment ➢ BEF to convert volume of extracted roundwood to total aboveground biomass (including bark) ➢ Mortality rate in natural and artificially regenerated forests	Improvements of default emissions and stock change factors, as well as development of the IPCC Emission Factor Database (EFDB) that is a supplementary tool to the 2006 IPCC Guidelines, providing alternative emission factors with associated documentation.
Three tier structure approach presented, but application for the selection of methods; AD and Emission Factors not provided.	Three tier structure for the choice of methods, AD and Emission Factors explicitly described.	Similar
Changes in carbon stock in biomass and soil carbon in a given vegetation, or forest type, not linked.	Biomass and soil carbon pools linked.	Similar

Figure 3.1: Evolution of the LULUCF sector in the IPCC guidelines. From the Task Force on National Greenhouse Gas Inventories Presentation at UNFCCC Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol (AWG-KP) Workshop on Methodological Issues, June 7th, 2008 (http://www.ipcc-nggip.iges.or.jp/presentation/NGGIP_AWG_KP.pdf)



3.3 INVENTORY AND REPORTING STEPS

The sequence of steps for inventorying emissions and removals needed for the National inventory report is outlined below:

1) Estimate the land areas in each land-use category for the time period required, drawing on the three approaches, described below, for representing areas in the GPG-LULUCF.

2) Conduct key category analysis, as described in Chapter 2, for the relevant categories. Within the categories designated as key, assess which non-CO_2 gases and carbon pools are significant and prioritize such pools in terms of methodological choice.

3) Ensure that the requirements in terms of emission and removal factors and AD appropriate to the tier level are being met; tier levels are described below.

4) Quantify emissions and removals and estimate the uncertainty in each estimate.

5) Use the reporting tables to report emissions and removals estimates. Utilize the worksheets where appropriate. Document and archive all information used to produce the national emissions and

removals estimates following specific instructions under each land-use category, carbon pool, non-CO_2 source, and land-use change (more information on reporting is provided in Chapter 6).

6) Implement quality control checks, verification, and expert peer review of the emission estimates following specific guidance under each land-use category, pool or non-CO_2 gas (more information on verification is provided in Chapter 6).

3.4 DEFINITIONS OF CARBON POOLS AND LAND USES

3.4.1 Carbon pools

The GPG-LULUCF provides the following definitions for the five carbon pools: aboveground biomass, belowground biomass, dead wood, litter, and soils. These definitions provide a generic representation of these pools occurring in a terrestrial ecosystem. Additional information, specific to forests, is included in Chapter 4.

Living Biomass:

- Aboveground biomass: All living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. Dead branches still attached to a living plant are included as part of the aboveground live tree biomass pool, but typically do not make up a significant fraction of the pool. Note that in cases where forest understory is a relatively small component of the above- ground biomass carbon pool, it is acceptable for the methodologies and associated data used in some tiers to exclude it—provided the tiers are used in a consistent manner throughout the inventory time series (as specified in Chapter 4).

- Belowground biomass: All living biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded, or measured as part of the soil carbon pool, because it is impractical to try to remove very fine roots and root hairs from the soil.

Dead Organic Matter:

- Dead wood: Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country. Typically, standing dead trees must be large enough to meet the definition of "tree" that is used for live trees by the country. Carbon stocks in lying dead wood are also called coarse woody debris.

- Litter: Includes all non-living biomass with a diameter less than a minimum diameter chosen by the country for dead wood (for example 10 cm, and possibly also a minimum length), lying dead, in various states of decomposition above the mineral or organic soil. This includes the litter, fumic, and humic layers. Live fine roots (of less than the suggested diameter limit for belowground biomass) are included in litter where they cannot be empirically distinguished.

Soils:

- Soil organic matter: Includes organic carbon in mineral and organic soils, (including peat) to a specified depth chosen by the country and applied consistently through the time series. Live fine roots (of less than the suggested diameter limit for belowground biomass) are included with soil organic matter where they cannot be distinguished from it empirically.

National circumstances may necessitate slight modifications to the pool definitions used here. Where modified definitions are used, it is good practice to clearly report them. This ensures that modified definitions are used consistently over time and demonstrates that pools are neither omitted nor double counted.

3.4.2 Land-use types

While this manual focuses on Measurement, Reporting and Verification (MRV) system requirements for forest land, all six top-level land categories defined by the GPG-LULUCF are briefly presented below:

Forest land

Forest land includes all land with woody vegetation consistent with thresholds used to define forest land in the national GHG inventory, sub-divided into *managed* and *unmanaged*, and also by ecosystem type. It also includes systems with vegetation that currently fall below, but are expected to exceed, the threshold of the forest land category.

Cropland

Cropland includes arable and tillage land, and agro-forestry systems with vegetation below thresholds used for the national definition of forest land.

Grassland

Grassland includes rangelands and pasture land that is not considered as cropland. It also includes systems with vegetation that fall below the threshold used in the forest land category and are not expected to exceed, without human intervention, the threshold used in the forest land category. The category also includes all grassland from wild natural grasslands, such as páramo, to recreational areas, as well as agricultural and silvipastoral systems, subdivided into *managed* and *unmanaged* consistent with national definitions.

Wetlands

Wetlands include land that is covered or saturated by water for all or part of the year (e.g., peatland) and does not fall into the forest land, cropland, grassland or settlements categories. Wetlands can be subdivided into *managed* and *unmanaged* according to national definitions.

Settlements

Settlements include all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with the selection of national definitions.

Other land

Other land includes bare soil, rock, ice, and all *unmanaged* land areas that do not fall into any of the other five categories. It allows the total identified land areas to match the national area, where data are available.

3.5 METHODOLOGIES FOR ESTIMATING EMISSIONS AND REMOVALS

As it is not possible to measure all emissions and removals, estimates can be made based on surrogate parameters that are associated with emission rates, such as the changes in carbon stocks before and after a change in land use. The generic form of the methodologies provided in the GPG-LULUCF is shown in Figure 3.2. Emissions estimates are equal to the product of all AD considered and their associated EFs. AD are changes in the area of land use, while EFs are the average amounts of emissions per unit-area of each type of activity.

The IPCC GPG-LULUCF (2003) and Guidelines (2006) allow for inventories with different levels of complexity, called "tiers." In general, inventories using higher tiers have improved accuracy and reduced uncertainty (Figure 3.3). There is a trade-off, however, as the complexity and resources required for conducting inventories also increase for higher tiers. A combination of tiers can be used (e.g., Tier 2 for biomass and Tier 1 for soil carbon), depending on data availability and the magnitude of expected changes in the pool.

Tier 1

Tier 1 methods are designed to be simple to use. The IPCC GPG-LULUCF (2003) and Guidelines (2006) provide equations and default parameter values (e.g., emission and stock change factors) so the inventory compiler does not need specific data for these equation parameters. Country-specific land use and management data are needed, but for Tier 1 there are often globally available sources for these estimates (e.g., deforestation rates, agricultural production statistics, global land cover maps, fertilizer use, livestock population data). The Tier 1 method alone, however, is unlikely to be sufficient for crediting under REDD+.

Figure 3.2: The IPCC basic equation for the estimation of emissions/removals

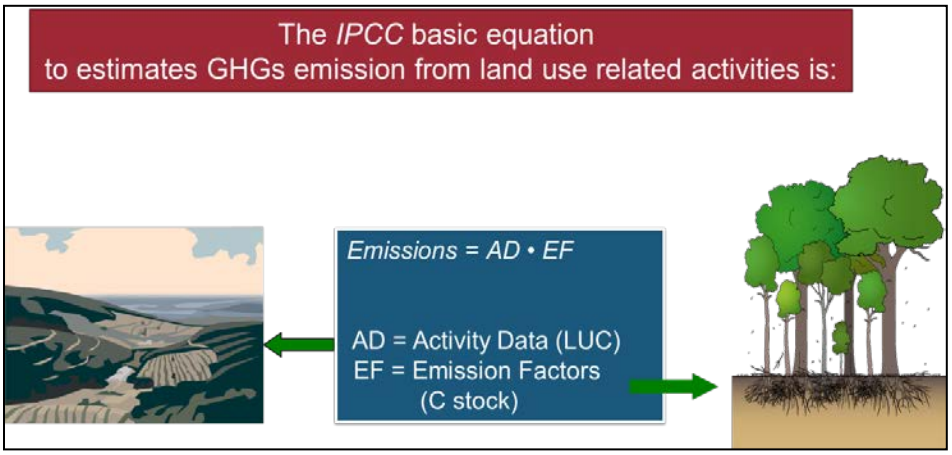
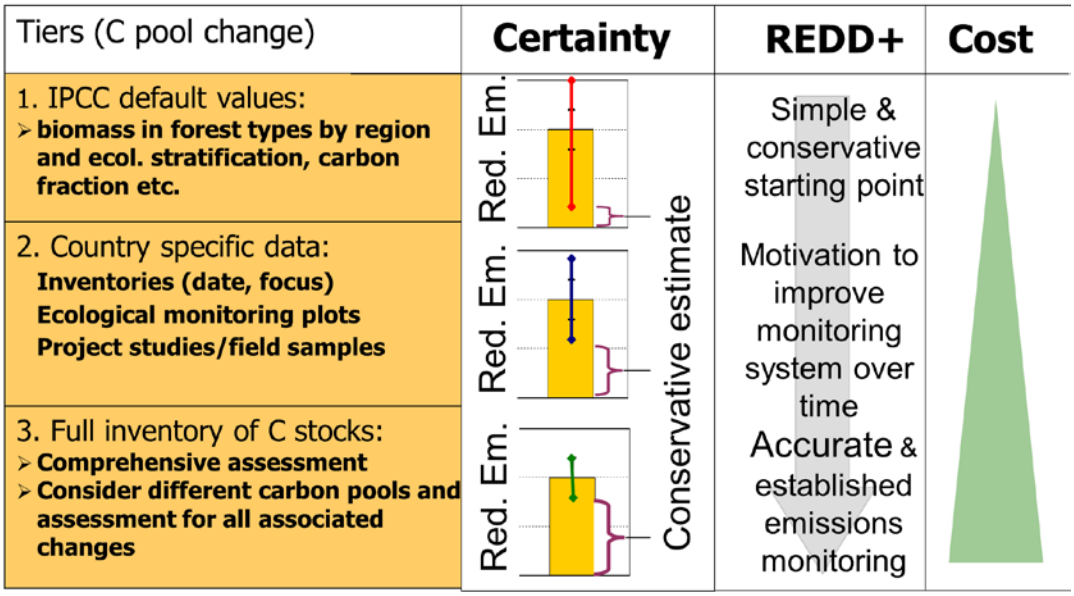


Figure 3.3: Key implications of using different tiers; note "Red. Em." stands for reduced emissions (adapted from GOFC GOLD, 2011)



Tier 2

Tier 2 uses the same methodological approach as Tier 1, but the emission and stock change factors are based on country or region-specific data. Country defined emission factors are more appropriate for the climatic regions and land-use systems in the country or region. Higher temporal and spatial resolution and more disaggregated land-use and management categories are used in Tier 2 to correspond with country-defined coefficients for specific regions and specialized land-use categories.

Tier 3

Tier 3 uses higher order methods, including models and inventory measurement systems tailored to address unique national circumstances. Assessments are repeated over time and employ high-resolution land use and management data, which are generally disaggregated at the subnational level. These inventories use advanced measurements and/or modeling systems to improve the estimation of GHG emissions and removals beyond Tier 1 or 2 approaches. (Angelsen, 2008)

As key categories have the most significant impact on total emissions, key categories should be addressed by at least Tier 2 methods, if possible, in order to improve the accuracy of the estimates (Figure 3.4). Other reasons for using a higher tier approach may be the need for improved detail in a particular sector; for example, the need to understand the abatement effect of a mitigation project.

3.5.1 Activity data

The IPCC Guidelines describe three different *approaches* for representing AD, or the change in area of different land categories (Figure 3.5). Note that approaches are specific to representing AD and should not be confused with the three inventory tiers discussed above. The three approaches include:

- Approach 1 identifies the total area for each land category. This information is usually provided by non-spatial country statistics and does not provide information on the nature and area of conversions between land uses (i.e., it only provides "net" area changes), for example 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 remote sensing mapping techniques.

It is likely that land-use changes under a REDD+ mechanism will be required to be both identifiable and traceable in the future. Therefore, it is likely that only Approach 3 will be useful for land tracking, and thus, REDD+ implementation.

Figure 3.4: Choice of estimation tier according to Key Category Analysis process (adapted from Maniatis and Mollicone, 2010)

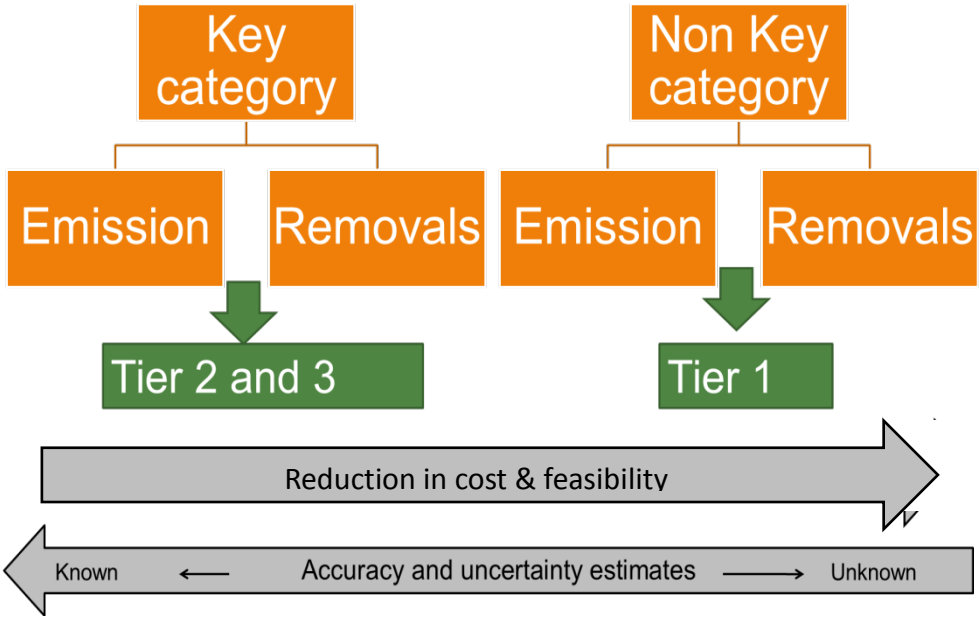


Figure 3.5: Different approaches for obtaining activity data

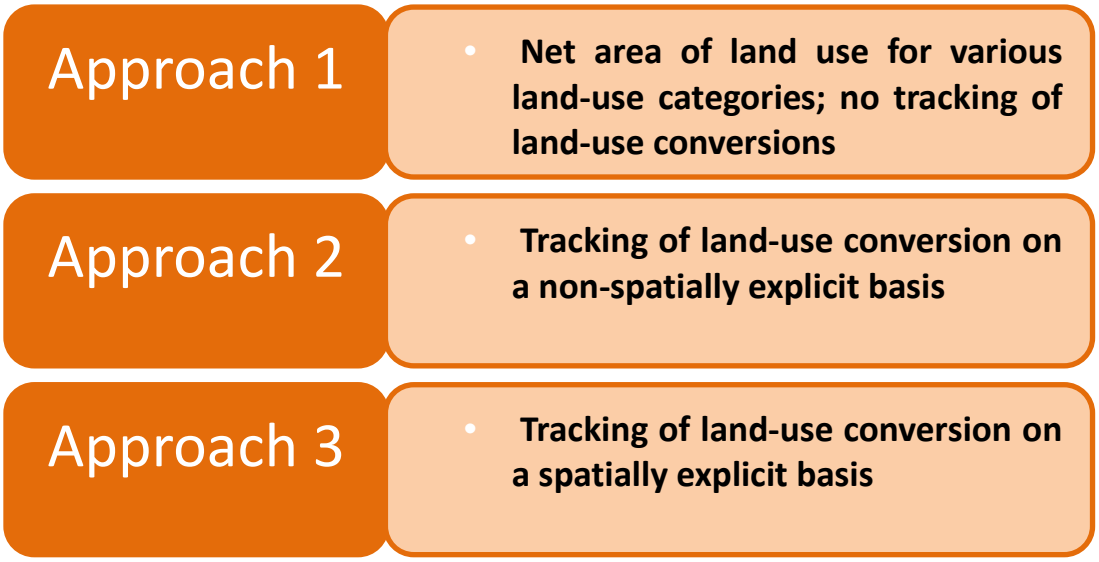
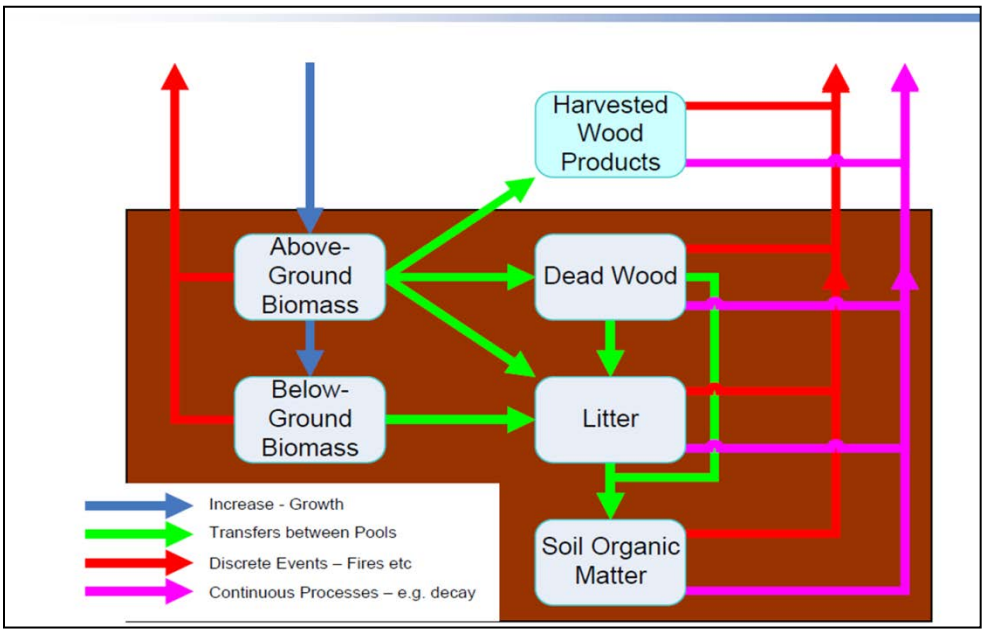


Figure 3.6: Carbon transfer among pools in a forest ecosystem



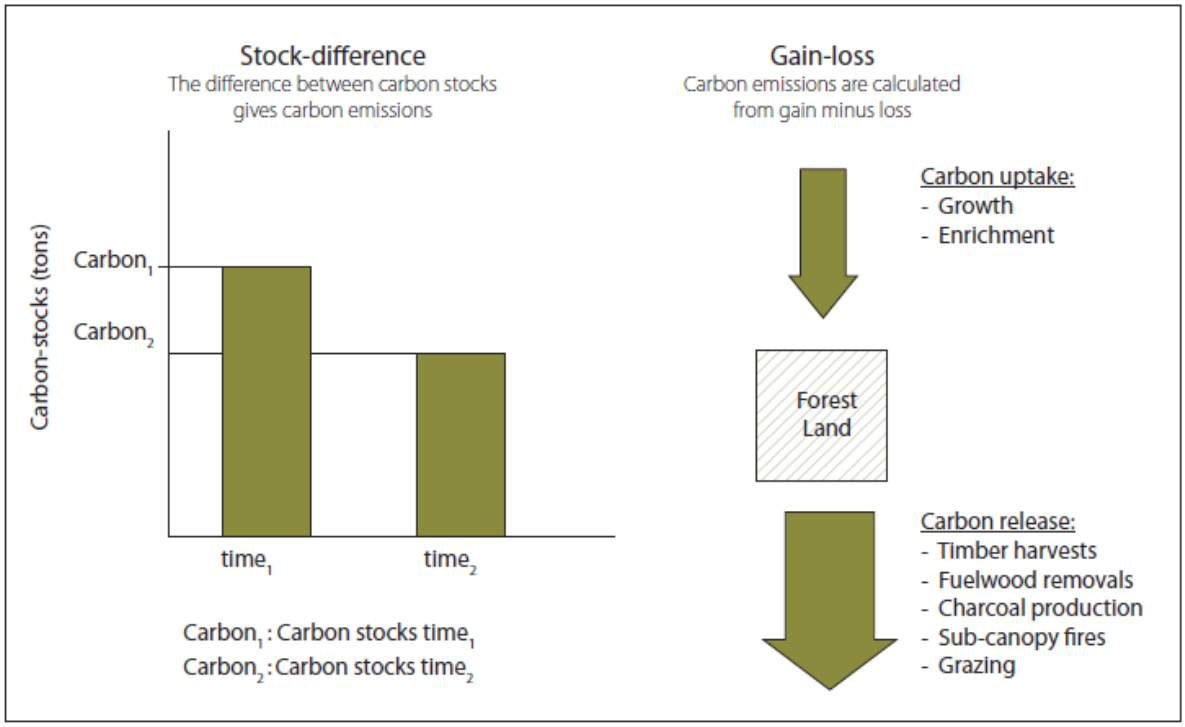
3.5.2 Emission factors

The first methodological requirement to be met for the national inventory report is the generation of country-specific estimates of the EFs for each key sub-category, i.e., different forest types or conversion of one forest type to a different category. To obtain such estimates and to comply with the UNFCCC completeness reporting principle, it is primarily necessary to develop a national forest inventory, or adapt an existing inventory, for REDD+ to provide estimates for the five IPCC forest carbon pools (aboveground biomass, belowground biomass, litter, deadwood and soil organic carbon). The carbon stock change estimates that a country will have to submit through its GHG inventory will also have to consider all the possible transfers between pools (Figure 3.6).

3.5.3 Methods to estimate emissions and removals

For land use, the IPCC recognizes two methods to estimate carbon emissions: the *Stock-Difference Method* and the *Gain-Loss Method* (IPCC, 2006). The stock-difference, or stock change, method estimates emissions by identifying the changes of carbon stocks at the beginning and the end of the period. The gain-loss method estimates emissions by identifying the amount of losses through disturbances, harvest, and gains through growth (Figure 3.7). Both of these simple calculation approaches assume that emissions and removals are equal to the total stock changes.

Figure 3.7: Two IPCC-recognized methods for estimating carbon emissions: i) stock-difference; and ii) gain-loss (Angelsen 2008)



The EFDB, described in Box 3.1, represents one source of EF data information. Additional sources of emission estimates include: 1) measured emissions and 2) complex calculations. Measured emission estimates are increasingly available due to the emission trading scheme requirements in some countries. However, using these estimates requires careful consideration, and compatibility with the unmeasured part of the inventory must be ensured, otherwise inconsistencies may arise.

Box 3.1: IPCC Emission Factor Database

One source of EFs is the IPCC Emission Factor Database (EFDB). The EFDB is a continuously revised web-based information exchange forum for EFs and other parameters relevant to the estimation of emissions or removals of GHGs at the national level. Internet queries of the database can be performed via the home pages of the IPCC, IPCC-NGGIP, or directly at http://www.ipcc-nggip.iges.or.jp/EFDB/main.php.

The EFDB is designed as a platform for experts and researchers to communicate new EFs or other parameters to a worldwide audience of potential end-users. It is intended to become a recognized library where users can find EFs and other parameters with background documentation or technical references. While experts and researchers from all over the world are invited to populate the EFDB with their data, the criteria for inclusion of new EFs and other parameters will be assessed by the editorial board of the EFDB. These procedures enable the user to judge the applicability of the EF, or other parameter, for use in their inventory; however, the responsibility of using this information appropriately remains with the user.

Emissions estimates may also come from complex models that the country has developed (Tier 3 method). The complex calculations include many parameters, (e.g., carbon density per species in a country). Some emissions occur over a period of years after the actual action, such as those from harvested wood products. However a country needs to ensure that the complex models are compatible with the IPCC Guidelines.

Lastly, data needs should be addressed. Particularly for land use, there is a range of data necessary for calculation. Various EFs and parameters, such as conversion factors of carbon content of wood, above ground biomass to total biomass, and growth rates, are required. To alleviate the lack of data, the guidelines provide default values for different regions and ecosystems. Nonetheless, it should be noted that some country-specific data tend not to change annually. Therefore, countries are encouraged to invest in finding country-specific data that are better suited to local circumstances. Such data may also be suitable for regional circumstances where a group of countries share similar ecosystems. Collaboration within the region for data could be seen as a cost-effective alternative.

Land uses can change on an annual basis, and therefore, AD on land areas can change on an annual basis. Thus, regular monitoring is required. The collection of AD should be conducted with the aim of generating representative, reliable, and consistent data over time, and could be accomplished through ground surveys, forest inventories, or using satellite data (GOFC GOLD, 2011). Table 3.2 summarizes the key elements to consider when estimating emissions and removals from the land-use change and forestry sector: i) the forest carbon pools (the EFs from forest ecosystems); ii) the changes in land use (AD); and iii) the carbon stock estimation methods.

Table 3.2: Key elements for the estimation of emissions and removals for the LULUCF sector

IPCC elements	Options	Implications
1. Forest carbon pools (Emission Factors)	**1. Tier 1**	➢ **High uncertainty but less expensive**
	2. Tier 2	➢ **Requires national data including a national forest inventory**
	3. Tier 3	➢ **Most accurate but more expensive and time consuming**
2. Land representation (Activity Data)	**1. Approach 1**	➢ **Not suitable for REDD+ due to the lack of accuracy**
	2. Approach 2	➢ **Not suitable for REDD+ because it is not spatially explicit**
	3. Approach 3	➢ **Suitable for REDD+, but requires rigorous analysis process and ground truthing**
3. Carbon stock estimation method	**1. Stock change**	➢ **2 series of forest inventories required**
	2. Gain - loss	➢ **1 forest inventory with carbon stock fluxes estimation**

3.6. REFERENCES

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4.0 GROUND-BASED INVENTORIES

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4.1 INTRODUCTION

According to United Nations Framework Convention on Climate Change (UNFCCC) guidance for reducing emissions from deforestation and forest degradation (REDD+), countries will have to establish national forest monitoring systems that quantify changes in land cover and terrestrial carbon stocks. It is preferable to do this using a combination of remote sensing for mapping the changes in land cover, and field-based forest carbon inventories for quantifying changes in carbon stocks in particular land cover types. Combining the land cover change maps with changes in stock in each cover type gives a calculation of forest-related greenhouse gas (GHG) emissions and removals.

A forest carbon inventory has multiple purposes, including providing accurate input into a national inventory, as well as a national communication of carbon emissions and removals from land use, and supporting the generation of GHG offset credits or national programs to mitigate emissions. When a forest carbon inventory can serve multiple needs, it will likely be easier to obtain resources to prepare the inventory and maintain support for continued work over time.

Forest carbon inventory data have substantial overlap with timber inventory data, and can serve other land management, wildlife, and land-use management needs. It may be possible to extend the use of collected data, or extend the geographic range of a forest carbon inventory and thereby jointly serve carbon inventory and other resource management needs. This type of data sharing can make the inventory more cost effective and ensure financing from more sources, since multiple information users can advocate for its continued funding. A good example is the Mexican National Forest and Soil Inventory, which carried out a process of consultations to identify the information that various users of the inventory would require. The national forest inventories supported by the Food and Agricultural Organization (FAO) National Forest Monitoring and Assessment program are another example. Besides the collection of information regarding timber species and volume, these inventories collect data on carbon stock, non-timber forest products and socio-economic indicators.[6] Unlike Afforestation and Reforestation projects, REDD+ activities may encompass vast areas of land, and should eventually encompass an entire country. There are economies of scale in forest carbon inventories, meaning that inventories covering more area become less expensive when the cost is calculated on a per-hectare basis.

4.2 CARBON POOLS AND THEIR MEASUREMENT

REDD+ forest inventories should quantify stocks of carbon in pools that might change significantly under the REDD+ program or under the REDD+ reference level. Other resource management goals may be addressed by having teams collect some additional types of data while doing their carbon inventory work.

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[6] See http://www.fao.org/forestry/nfma/47655/en/

While the different carbon pools are described in Chapter 3, the information below highlights considerations specific to forest inventories.

All inventories should measure live trees above a modest size because this is typically the largest biotic carbon pool in a forest that would be lost via deforestation. If forest land is converted to agricultural use or developed use, substantial amounts of soil carbon may be lost, and thus monitoring of soil organic carbon stocks may be warranted. If there is substantial disturbance of forests via degradation, it may be important to measure dead wood carbon stocks.

4.2.1 Aboveground biomass

In a forest, aboveground biomass will emit the most carbon upon conversion to non-forest. However, in some systems, soil carbon loss resulting from conversion of forest to agricultural cropland can be greater than emissions from aboveground biomass. Table 4.7 in the Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines provides default average aboveground biomass values according to forest types and continents.

An example of a default set of size categories is one where the tree category has a diameter at breast height (DBH) of at least 10 cm, and the shrub/small tree category includes woody plants at least 10 cm, 50 cm or 1 m tall. Typically, smaller woody plants and non-woody plants are excluded or are measured separately from larger woody plants. To increase sampling efficiency, there may be sub-categories such as small trees that are 10-40 cm DBH and large trees that are greater than 40 cm DBH. To accurately estimate the forest carbon stock of live biomass, the inventory should include all tree species, tallying trees with diameters of at least 10 cm. Forest inventories give limited reliability in estimation of carbon stocks and stock changes if the inventories only count commercial species or trees over 30 cm DBH (GOFC-GOLD, 2010).

4.2.2 Belowground biomass

Belowground biomass is an important carbon pool that may equal 25 percent or more of the aboveground biomass in many forests. As discussed in Chapter 3, fine roots are often excluded, or measured as part of the soil carbon pool due to the difficulties in manually separating them from soil. The boundary between fine and coarse roots depends on the method used to estimate the belowground biomass. The IPCC recommends 2 mm diameter (Smith et al, 2007), but measuring root biomass is time consuming and expensive. Therefore, REDD+ implementers may choose to apply a Tier 1 approach which uses the default root-to-shoot ratios provided in Table 4.4 of the IPCC 2006 Guidelines. To obtain the belowground biomass, multiply the aboveground biomass by 1 + root: shoot ratio.

4.2.3 Dead wood

Dead wood, a sub-component of dead organic matter, includes standing and lying deadwood. Standing dead wood is typically measured along with living tree biomass. By convention, dead woody stems where the long axis of the stem is within 45 degrees of vertical are classified as standing dead and stems where the long axis is more than 45 degrees off vertical are classified as lying dead wood. A typical minimum piece size for coarse woody debris is 10 cm in diameter and sometimes there is also a minimum length requirement that pieces be at least 1 m long. Pieces that are not large enough to be classified as coarse debris are classed as fine debris. A common minimum size of fine debris pieces is 1 cm, with smaller pieces being classified as litter. If litter is measured, the boundary definition must correspond to the smallest piece of woody debris, so that any piece of material fits in exactly one category, and is neither double-counted nor excluded.

4.2.4 Litter

Litter, better described as the "forest floor," includes fine woody debris, foliage and twigs that are on the ground and not attached to a plant stem, as well as live fine roots that are above the mineral or organic soil. A humic layer of organic soil is the decomposed remnants of vegetative material and is typically not included in the litter pool. It typically is included in the soil pool, but if this pool occurs infrequently it may be included in the litter pool. Fine woody debris is small pieces of dead wood. By convention, material less than 1 cm in diameter are defined as litter. However, the litter pool may be defined as including fine woody debris up to 10 cm in diameter, particularly if there is no fine woody debris pool. Whatever boundary is chosen, the same boundary must be used for the maximum size of pieces in the litter pool and the minimum size of pieces in the woody debris pool.

For some forest types, litter tends to decompose easily, and as a result, may not be worth measuring since the pool is not typically large. However, if decomposition is slowed by factors such as cold temperatures, moisture saturation, low pH, or nutrient limitation, an organic layer may form. Examples of this include peat and muck soils; peat is a buildup of minimally decomposed plant material, while muck is black, decomposed organic material. If a significant decomposed organic layer is present between the litter and the mineral soil, it should be measured separately from the litter and the mineral soil carbon pools.

4.2.5 Soil organic matter

As discussed in Chapter 3, this category includes all organic carbon in mineral and organic soils to a specified depth. Typically, there is no inorganic carbon in soils, except for sites that are so arid that few trees are likely to grow and sites with carbonaceous soils such as limestone. Although there are often measurable amounts of soil organic carbon down to depths of several meters, carbon is generally counted if it is in the top 20 or 30 cm of soil, but some projects have measured soil carbon to 1 m depth or more. The density of soil carbon decreases with depth, and the amount of effort required to sample soil carbon increases with depth. Soil carbon models generally are not calibrated to address depths greater than 20 cm.

Total soil carbon stocks are often as large as, or larger than, woody biomass carbon stocks. If there are small or modest degrees of disturbance of the forest, soil carbon stocks are unlikely to change much. As a result, many projects or programs that maintain existing forest do not measure soil carbon stocks because the stocks are assumed to be constant. However, in the case of forest clear-cutting and conversion to farmland, soil carbon stocks may have large changes and should be measured, particularly if the agricultural activities include plowing.

The threshold size of roots and dead wood to be included in the soil carbon category must correspond to definitions used in the live belowground biomass and dead wood categories. By convention, live roots less than 2 mm in diameter are often classified as part of the soil carbon pool, and live roots of 2 mm or greater diameter are classified as belowground live biomass. There is less standardization of the definitional boundary between soil carbon and woody debris but typically the boundary is defined as a specific piece size or degree to which pieces are buried. According to the IPCC definition, only the organic carbon should be accounted for, so laboratory tests that do not differentiate organic from inorganic carbon should be avoided, if inorganic soil carbon is likely to be present.

If measuring soil carbon, a key decision is the depth to which soil will be measured. In undisturbed systems, there is more soil carbon per centimeter of depth at the surface than there is at 40 or 100 cm below. At depths of more than one to three meters, the density of soil carbon is low, and changes in the stock are slow, but the total amounts can be significant because the mass of soil is so large. Most of the change in soil carbon happens near the surface. A decade or two of plowing typically removes 40 percent of the soil carbon, which is often the top 20 cm. When switching from plowing to trees or no-till cropping, it is possible that half the soil carbon gain in the first five to 10 years will be in the top 10 cm of soil.

To capture much of the carbon stock change that results from land management changes, while limiting sampling effort, many inventories sample only the top 20 or 30 cm of soil. This shallow sampling is especially common for inventories focused on detecting carbon stock increases. Larger changes in percentage terms are easier to detect with sampling. Much of the gain in soil carbon in the first few years of conversion from crops to forest is in the top few cm of soil. Thus the gain in percentage terms is greatest when only the top few cm are measured. In conversion of tilled cropland to grassland there can be significant carbon gains to more than 1 m of depth and it may be worth the effort to do deep sampling.

When measuring soil carbon loss upon conversion of forest or grassland to cropland with plowing, the percentage change in carbon stock may be large, even when measuring to significant depths, such as 50 or 100 cm. As a result, avoided deforestation projects may find it worth the effort to sample soil much deeper than 30 cm, such as to a depth of 1 m, to be able to claim credit for avoiding emission of deeper soil carbon.

4.3 THE GAIN-LOSS AND STOCK-DIFFERENCE METHODS

As discussed in Chapter 3, the IPCC recognizes two methods to estimate carbon changes: the Gain-Loss method and the Stock-Difference method (IPCC, 2006).

The Gain-Loss (or Process-Based) method requires the initial measurement of the carbon stock and subsequently measurements of:

- Increases in stocks in forest remaining forest (vegetation growth);
- Emissions from natural mortality;
- Emissions from disturbances (mortality due to wind, fire, diseases); and
- Emissions from wood removals due to logging and fuel wood collection.

The Gain-Loss method requires relatively accurate measurement of the extent of disturbances and while national records will account for timber extracted legally, they will not be able to quantify subsistence and illegal logging.

Usually, the Gain-Loss method is applied when using an IPCC Tier 1 approach, which requires no new data collection to generate estimates of forest biomass. Using the Tier 1 approach:

- Data on forest biomass and mean annual increment are obtained from the IPCC Emission Factor Data Base corresponding to broad continental forest types (e.g. African tropical rainforest) and
- Data on emissions are obtained from national registries of wood removals and disturbances. A Tier 1 approach thus provides estimates with a large error range (+/- 50 percent) for forest carbon stock in developing countries (GOFC-GOLD, 2010).

It is expected that negotiations on REDD+ guidance will require at least Tier 2 approach due to the error potential of Tier 1.

In contrast, the Stock-Difference (or Stock-Change) method is applied when using an IPCC Tier 3 approach, where changes in forest carbon stocks are estimated through repeated measurements in the field (e.g., DBH and height measurements every 5 years) and locally calibrated allometric equations. The measurements made at different times must be consistent with each other, or the stock change estimates will not be accurate. An intermediate Tier 2 approach would also use DBH measurements of trees, but combine them with general allometric equations or IPCC default biomass conversion and expansion factors (BCEFs).

Different tiers can be applied to different forest carbon pools according to their importance. The pools with the largest expected changes should be quantified precisely to obtain an accurate estimate of net sink or

emission. Live tree biomass is often the pool that can change the greatest. Thus, in most cases the above and belowground biomass should be quantified using more accurate and precise Tier 3 methods. If emissions from the litter, deadwood and soil carbon constitute less than 25 percent of deforestation emissions, a lower tier would be justified to measure these pools (GOFC-GOLD, 2010). If forest is cleared for agriculture and the soil is tilled, soil carbon emissions can be as great as or greater than biomass emissions, and soil carbon stock changes should be quantified, rather than using default data and a Tier 1 approach.

The following sections mostly focus on approaches using the application of a Tier 2 or Tier 3 Stock-Difference method.

4.4 CONCEPTS AND CONSIDERATIONS IN INVENTORY DESIGN

Many possible inventory designs can be used to estimate forest carbon stocks. The goal is to choose an efficient design that achieves the desired level of precision at a minimum cost. In general, the process of designing an inventory involves a sequence of steps:

1) Needs assessment: define what needs to be known as a result of the inventory
2) Sample design selection process: based on logistical considerations and physical conditions
3) Alternative plot design selections
4) Cost assessment: based on a calculation of the number of plots needed and the cost of applying different combinations of plot and sample designs to find a design that meets the specified needs at an acceptable cost

4.4.1 Needs assessment

The first two decisions in designing an inventory are choosing what is to be estimated, and over what geographic area. The geographic scope might be a particular block of land amounting to only a few dozen hectares, an entire country, or something in between. Initially, REDD+ monitoring activities may also only focus on lands that are classified as forest, or as managed forest. A comprehensive terrestrial carbon accounting system should address all types of land within the geographic boundaries of the nation or jurisdiction that the accounting system serves. Initially, some land cover types or land uses might only be mapped without measuring carbon stocks. Ultimately, monitoring efforts are likely to be focused on forest lands, especially those most susceptible to deforestation and degradation.

The next decision is whether there are sub-divisions within the total area where extra information is needed. For example, a country may wish to understand trends for specific regions or forest types. Producing accurate estimates of stocks and changes for all the various strata will significantly increase costs.

A common way to reduce sampling error is to measure a greater number of plots. The number of plots needed to achieve a given level of statistical precision is mainly a function of the variability within the forest being surveyed. Over large areas, such as sub-national regions, the size of the area has relatively little effect on the number of plots needed to measure carbon stocks with a specified level of precision. If the forest is highly variable, it should be stratified into homogeneous types. Stratification should be based on available surrogate data that are believed to be informative of potential variability in forest biomass. These can include data on climate zones, vegetation maps or research on global biomass distribution.

The different aspects of inventory design interact, and the goal is to have the interactions be complementary, not in conflict. One of the most fundamental interactions is between plot size and the number of plots to be inventoried. More plots give more statistical precision in estimates, but fewer larger plots have less plot-to-plot variability. To limit the costs of getting to plots, it may be desirable to design the inventory with fewer, larger plots rather than a large number of smaller plots. Another consideration is that if the goal is to

accurately quantify small changes in carbon stocks from year to year, permanent plots may be necessary. The implications of any particular inventory design should be understood before one is selected. It is recommended that to inform the design of the inventory, the variability as a function of plot size should be assessed. Estimating the cost of travelling to more remote plots and the cost of measuring smaller versus larger plots is also recommended.

4.4.2 Sampling design selection and purpose of forest stratification

Sampling must be unbiased to ensure that resulting inventories will be reliable. There are many options available for developing a sampling design. Four common approaches are: i) systematic sampling, ii) stratified sampling, iii) simple-random sampling, and iv) cluster sampling.

Many national inventories of forests use a systematic sampling design, where regularly spaced plots are measured. A systematic sample ensures that all geographic areas are equally represented, and is especially useful if little is known about forest conditions or dynamics. However, stratified sampling often provides knowledge at a lower cost than systematic sampling. Simple random sampling is rarely used in national inventories.

Systematic Sampling

Typically, systematic sampling involves laying a regular grid over the geographic area to be inventoried, and locating plot centers at the grid intersection points. The spacing of the grid lines is calculated so that the desired number of plots can be placed in the area. Many people find systematic sampling attractive because it gives equal emphasis to all parts of the area being sampled. A variation on systematic sampling is to randomly locate one plot within each cell defined by the grid lines. Systematic sampling can be expensive in terrain with limited access because plot teams will need to reach many very remote locations.

An example of a recent national forest inventory performed using systematic sampling is the Integrated Land Use Assessment (ILUA) carried out by the Zambia Forestry Department (2005-2008). The ILUA set up 221 tracks (each track has 4 sampling plots) systematically across the country at 50 km distances. Mexico provides another example, where the National Forest and Soil inventory established a systematic sample grid of 25,000 geo-referenced permanent points. Each point contains four sites of 400 m2. From 2008 onward, about 20 percent of the points have been re-measured, such that all points are monitored once every five years (GOFC-GOLD, 2010).

Stratified Sampling

Stratified sampling is accomplished by dividing the sampling area into relatively homogenous sub-areas, and separately sampling each sub area. Stratification increases efficiency of sampling, giving more precise estimates for the same or less effort. Within each stratum, a systematic sample or simple random sample is conducted. Carbon stock (or stock change) is estimated for each stratum, then the stocks of the strata are summed to estimate the stock (or stock change) of the entire area.

While many approaches to stratification exist, it is common to stratify by ecotype or forest type. This approach to stratification increases statistical power, giving a more precise estimate of carbon stocks for a given number of plots of a given design but also increases the likelihood that plots will be similar to each other. For a given number of plots, having lower variance between plots gives a higher probability that the total carbon stock will be close to the carbon stock estimated from the sampling. Homogeneous strata need few plots to precisely estimate their carbon stocks and, therefore, sampling efforts can be focused towards more variable ecotypes or forest types.

Inventories for monitoring change in carbon stocks over time can be optimized by allocating more effort to areas with larger changes in carbon stocks. This would mean stratifying by the expected future change in carbon stock, and allocating more sampling effort to strata that are expected to have greater change over time

(decrease or increase). If permanent plots are used, a challenge to weighting by expected change in carbon stock is that the optimal sampling intensity for each stratum will change over time. Inventory designers can guess what the optimal sampling will be in the future and assign enough plots to meet precision targets. It is possible to change the intensity of sampling over time — even with permanent plots — but the statistics for getting comparable carbon stock estimates over time are complex and beyond the scope of this manual. Despite the possible long-term mathematical complexity, stratifying by expected change in carbon stock can be desirable, and may be essential if net changes in stocks are small compared to total stocks. The goal is to "block" differences into different strata.

Simple Random Sampling

A simple random sample approach randomly locates plots within a study area. One reason to use a simple random sample is to avoid bias that might be introduced by systematic sampling, where the sampling grid might align with a pattern in the landscape and result in a biased estimate. However, the utility of simple random sample approaches is limited because they are only efficient for relatively homogeneous areas, or where there is no reasonable way to map the forest into strata. Thus, a stratified-random sample is more common.

Cluster Sampling

Cluster sampling uses clusters of plots where the plots in a particular cluster are relatively close to each other. Cluster patterns can be regular or random. An example of a regular cluster pattern would be five plots per cluster where one plot is centered on the central point of the cluster, and the remaining four plots are located with plot centers 200m away from the cluster center, in the cardinal directions. The distance between the plots within the cluster should be large enough to allow very little autocorrelation between the plots. Data is analyzed using cluster means, not the values observed on individual plots.

For a given number of plots, cluster sampling gives less statistical precision than a simple random sample. However, cluster sampling can result in reduced travel and administrative costs.

Stratifying

The IPCC recommends stratifying by climate, soil, ecological zone, and management practices (Vol. 4, Chapter 3.3.2.1).When choosing strata, designers should consider what is known about the forest and the dynamics of carbon stock change. Within each stratum, the goal is to have relatively homogeneous forest, or forest with the same carbon stock dynamics, but for this forest to be different from other strata. Of equal or more importance, the cost of placing large numbers of plots in remote inaccessible forest areas may be prohibitively expensive and/or logistically impossible. Thus, the sampling intensities in these areas may be selected to be less than an accessible area. In this case, areas with different sampling intensities constitute different strata.

To stratify a country's forest it is first necessary to have a current map of the dimension being used to stratify. This may be a national forest benchmark map or some other valid map source. To stratify within each land-cover type, one can use various Geographic Information System (GIS) data on elevation, soils or parameters. If no previous information on forest types exists in the country, the stratification can be done initially using global ecological datasets, such as maps of Holdridge life zones (http://geodata.grid.unep.ch/), World Wildlife Fund Ecoregions (http://www.worldwildlife.org/science/data/terreco.cfm), and FAO ecological zones (http://www.fao.org/geonetwork/srv/en/main.home).

If the goal of an inventory is to precisely quantify changes in forest carbon stocks, allocation of plots should be weighted toward areas where carbon stocks are susceptible to decrease from degradation or deforestation, or increase from regeneration.

4.4.3 Plot design options

Plot design determines what can be deduced from forest measurements. All data needed for analysis must be addressed in the plot design. Sometimes it is effective to work backwards from what is to be gained from the inventory work, through the analysis steps, back to the plot data, and thus determine what data should be collected.

Plot size affects the variability of carbon stocks observed on different plots, and the variability used in calculations of plots needed for the inventory will imply an approximate plot design. When designing an inventory to achieve a target level of precision, it is recommended to analyze actual plot data to estimate the variability that will result if different plot sizes are selected for different sizes or types of trees.

Including detailed location specification or complementary types of data can assist in checking and correcting errors and other problems. For example, recording the location of individual trees within a plot helps check for trees missing from the measurement, check cruising the accuracy of measurements, and relocating plot centers.

In a forest inventory, typical options for a plot design are:

- Points (dimensionless): a dot grid over a land cover map can be used to assess the areas that are forest or non-forest (dichotomous variables), different forest types (categorical variables) or variable radius "prism" plots where a tree is determined to be in or out as a function of the ratio of its diameter to distance from plot center. Point plots can be very efficient for one-time inventories or for inventories where permanent plots are not used, and strata change from one inventory to the next.

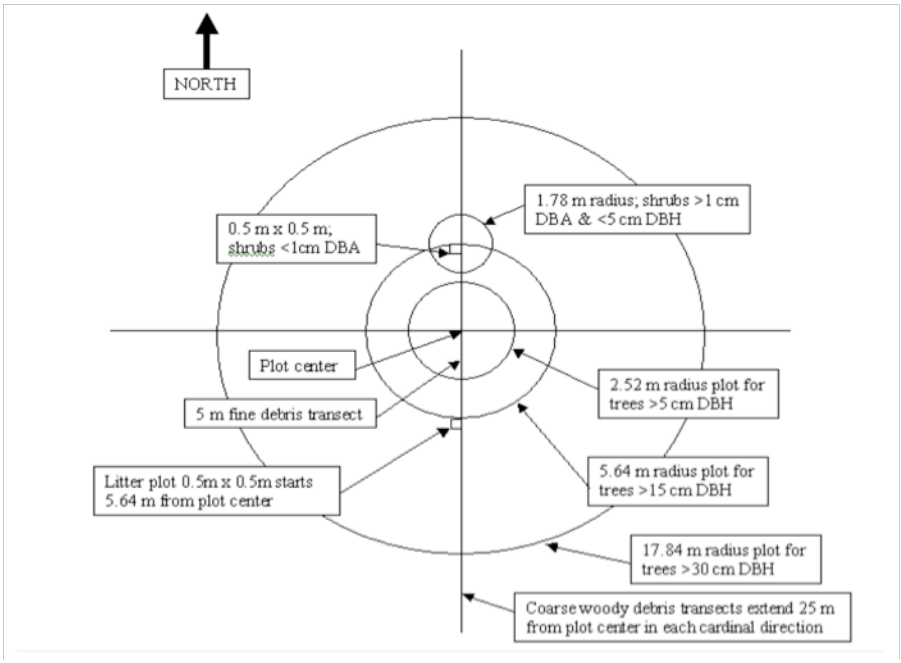
- Lines (one dimensional): on a sample line[7] it can be observed how many features intersects the line. This method can be used to calculate the volume of coarse woody debris.

- Areas (two dimensional): all the trees found on a determined area are measured. Often these plots are called "fixed area" plots because the size is fixed. Typically, area plots are circular or rectangular.

Plots of different sizes or different types may be nested with each other to achieve an efficient design for measuring different forms of biomass that occur in the forest (see Figure 4.1). Large trees are widely spaced, and large plots are needed to ensure that multiple large trees will occur in each plot. For an inventory of a large area, a "large" plot is often between 0.05 and 0.2 ha, but some projects have used plots as large as 1 ha. Small objects tend to occur more frequently, and it is efficient to measure only a few of them. As a result, plots for measuring seedling trees typically are only a few square meters in area, and plots for measuring litter are typically less than a square meter. Transects can be combined with fixed area plots or point plots. Transects are efficient for measuring biomass of fallen trees.

[7] It is important to notice that a sample line plot design isn't the same as a transect plot design. A transect plot design, even if long and narrow, is an area (two-dimensional).

Figure 4.1: Sampling design including nested plots and line samples to measure the different types of carbon pools. From Smith et al (2007).



Plot size is different for the different plot types. For line plots, the key issue is length. For prism plots, the key issue is the prism factor, which is the ratio of diameter to distance from plot center that determines whether or not a tree is measured. For area plots, plot size is simply the area encompassed by the plot. These issues determine the "size" of the plot, and how many trees are included.

Plots can have different shapes: circular, square, or rectangular. Normally, it is preferable to have circular plots because they have the smallest perimeter for the same area, reducing the amount of border trees. In contrast, in forests where visibility and penetrability is limited, transects tend to be preferable to facilitate accessibility to the entire plot and ensure that trees do not remain uncounted. Also, transects tend to cover more site conditions, increasing the variability within plots.

The typical diameter distribution in a natural forest has a negative J shape (i.e., a very high number of small trees and fewer larger trees). Nested subplots allow increased efficiency in plot measurements. Another plot design option, frequently used in private timber industry surveys, is the variable radius plot or Bitterlich sampling. Using a device with a defined opening angle, such as a relascope, a wedge prism, or a dendrometer, one stands at a sample point and sweeps around 360 degrees. All trees that appear wider than the opening angle are counted. In principle, it is similar to nested sample plot, where only the smaller trees that are closer to the sample point will be accounted for, while bigger trees will be included even if more distant. In this approach, the basal area is estimated by counting the number of trees and multiplying by a calibration factor, or a basal area factor. Establishing and collecting data from variable radius plots is fast, however this method only yields estimates of basal area. Therefore, this information is useful only if it can be correlated to the volume of the aboveground biomass of the forest stand.

The measurement parameters depend on the carbon pools of interest and the allometric equations that will be used to convert tree measurements into biomass. When considering taxa-specific equations or ones that use height, one should consider both the availability of people who can identify the species and the additional cost of tree-height measurements.

Dead wood is divided into standing and lying dead wood. Data on standing deadwood are collected as part of the tree inventory (see Aboveground biomass) and recorded as deadwood since their density often differs from live trees (Lackmann, 2011). It is relatively easy to measure lying deadwood.

All inventories should have written standards specifying the maximum inaccuracy allowed for each piece of data. Maximum allowable errors should be developed in consultation with experts in both field work and data analysis. Particular attention should be given to possible errors that would have a large effect on final carbon stock or stock change estimates.

Slope correction for fix area plots

Forest inventories report measurements over horizontal areas. Slope corrections, where plot size is increased, can account for the fact that distances measured along a slope are smaller when projected into a horizontal map plane. These need be applied only if the slope is greater than 10 percent. In this case, a circular plot, for example, is increased by multiplying the radius by $\sqrt{(1/\cos \alpha)}$, where α is the maximum slope angle (Lackmann, 2011).

Permanent plots versus temporary plots

Permanent plots, which are re-measured periodically (e.g., every five years), allow for estimating the stand growth and disturbances with more precision and can therefore quantify small increases or decreases in stocks. Typically, when forest carbon is being measured, it is necessary to detect the magnitude of change in carbon stocks over a short period of time such as five or fewer years. Note that weather and disturbance events can cause annual changes in forest carbon stock that are larger than anthropogenic changes, and attempting to quantify annual changes in forest carbon stocks resulting from human activities can be confounded by weather and wildfire.

When establishing permanent plots it is good practice to increase the minimum number of plots for the baseline by 5 to 20 percent, providing a cushion in case some permanent plots cannot be relocated or land cover changes. There is a risk that plots, when visibly marked, may be treated differently by forest users or plantation managers. Consequently, it may be desirable to mark plot centers with monuments that are not visible to the human eye, such as placing a metal stake completely in the ground, for identification with a metal detector (Smith et al, 2007; Diaz, 2011).

Temporary plots are typically used in timber inventories. An advantage of temporary plots is that both stratum boundaries and the intensity of sampling can be easily changed over time.

Table 4.1: Carbon pools and associated methods for carbon stock estimation using field data from ILUA (adapted from Kewin and Kamelarczyk, 2009).

Carbon pool		Method used for carbon stock estimation with ILUA data
Biomass	Aboveground	Estimates correspond to IPCC 2006 guidelines Tier 2 or 3. Carbon fraction of biomass equal to 0.47.
	Belowground	Estimates correspond to IPCC 2006 guidelines for Tier 1, using IPCC root to shoot ratio default values. Below/aboveground biomass fraction = 0.28 for tropical dry forest with above ground biomass > 20 tons ha^{-1}. Calculated for all land-use categories. Carbon fraction of biomass equal to 0.47.
Dead organic matter	Deadwood	Estimated in similar manner as for above ground biomass. Calculated for all land-use categories. Carbon in stumps and in dead biomass below ground (roots of dead trees and stumps) have been excluded due to the lack of sufficient data.* Carbon fraction for dead wood has in the estimates been assumed to be equal to that of living biomass (0.47). However, studies suggest a carbon fraction of deadwood to be closer to 0.34 (Pearson & Brown 2005).
	Litter	Estimates correspond to IPCC 2006 guidelines for Tier 1. Evergreen = 5.2 tons carbon ha-1, deciduous and other natural forest = 2.1 tons of carbon ha^{-1}. For semi-evergreen forest (miombo), the Frost (1996) litter estimate has been applied (5.48 tons of biomass ha^{-1}) converted to carbon using 0.47 as carbon fraction. Carbon in the litter pool has only been calculated for forest land-use categories.
Soil carbon		Using IPCC look-up tables for tier level 1 estimations. All areas are assumed to contain mineral soils (31 tons of carbon ha^{-1}). Soil carbon has only been calculated for the land-use categories of forest and other wooded land where it is being assumed (following the tier 1 approach) that no change in soil carbon occurs with change of management.

4.4.4 Calculating the number of sample plots and cost considerations

The goal of sampling is to reach a desired precision of the estimate of carbon stocks for an acceptable cost. Purely by chance, plots can be located in places with more or less biomass than the forest average. If many

plots are sampled, it is unlikely that the average biomass on the plots is very different from the true average biomass of the forest.

Some general principles should guide plot design and sampling design. First, more plots yield lower sampling errors. To reduce uncertainty by half can require four times as many plots. Thus, getting extremely precise estimates may become expensive. Second, the statistical precision of a biomass estimate depends on the variability of the forest. The greater the variability of the forest, the more plots will be needed to obtain a given level of precision.

The key input to estimating the number of plots needed to obtain a given level of precision is the variation between plots, calculated as the coefficient of variation (CV). The CV is a measure of how different plots are from each other. Technically, the CV is the standard deviation divided by the mean. These statistics are discussed in Section 4.7.5 on calculating uncertainties. Table 4.2 shows the final results of a hypothetical example of estimating sampling sizes needed to reach specified sampling errors. In this case, the number of plots required to meet an increasing level of precision increases by four to reduce the uncertainty by half. On the other hand, the number of plots is relatively independent from the size of the area. Plot numbers in stratified sampling are dependent on the variability of the carbon stock in each stratum and the level of precision required, but are not dependent on the spatial extent of the project (Diaz and Delaney, 2011). CV can be estimated from prior surveys that use a similar plot design in similar forests. If no prior surveys exist, a pilot study should be undertaken to estimate the CV. For small plots in forest with gaps, the CV can be well over 100 percent. In fully stocked plantations, the CV can be less than 30 percent.

Larger plots may average out some of the fine-scale variations in forests, giving less plot-to-plot variability than smaller plots. When calculating the number of plots needed, one must choose an estimate of variability between plots. The chosen variability implies a plot size. For example, a level of variability might assume that almost all plots contain at least four large trees and that very few plots will contain gaps with few or no medium or large trees. Thus, when choosing plot size, the analyst will have to consider the density of large trees in the forest and the range of sizes of gaps, and choose a plot size that is large enough that with the clumped spacing of trees in the forest, most plots will have the required number of trees. At some point, the cost of increasing the size of existing plots no longer yields a significant reduction of variance when compared to that which could be achieved by adding more plots to the sample. There is a theoretical optimal balance between plot size and sample size that can be achieved through some combination of field experiments or prior knowledge. However, when sampling large areas, travel costs can have more effect on total cost than the number of plots, and for a given amount of money, greater statistical precision might be obtained by using fewer and larger plots than the theoretical optimum calculated without considering costs.

There are other more complex sampling systems that may or may not give more power for a given level of effort. However, their complexity is beyond the scope of this manual. Options include stratified random cluster sampling, two-stage sampling and ranked set sampling. Many inventories aim to keep crews continuously employed but only re-measure plots once every five years. In such a case, 20 percent of plots would be measured each year, with 100 percent of plots measured every five years. This is an example of a panel sample. If any of these more complex sampling systems are considered, a statistician should be consulted to ensure that data analysis procedures are correct.

Table 4.2: Example of the number of sample plots needed to achieve specified sampling errors with simple random sampling. The significance level is 95 percent; for a large area.

Coefficient of Variation	+/-20 Acceptable Error	+/- 10 Acceptable Error	+/- 5 Acceptable Error	+/- 2 Acceptable Error
100%	98	392	1568	9801
50%	25	98	392	2450
20%	4	16	63	392
15%	2	9	35	221

Locating plots

As noted above, a sample design can be random or systematic, and approximate plot locations are specified by the design. If sampling crews choose plot locations they almost always choose locations that give a biased sample. They sample in locations they are familiar with, or locations that are easily accessible, or locations that fit their image of what kind of vegetation is supposed to be present. The resulting sample is biased. An analyst cannot know how the biased sample differs from the true mean. Therefore, to avoid possible location bias, plots should be located prior to going to the field based on a desktop GIS analysis. Further, best practices when collecting Global Positioning System (GPS) data should be used, taking into account the published accuracy of the receiver type. And since errors can occur with GPS locations, there must be a method for relocating plots that does not rely only on consumer-level GPS readings. Many inventories use monuments to mark plot centers. The monument must be something that is unlikely to be removed over time. For example, many inventories drive a section of steel rebar completely into the ground at the plot center, and re-find the rebar with a metal detector. Aligning tree tags or painted markings on trees toward the plot center can assist in relocating plot centers, as long as the tags are not commonly removed by people or animals, and as long as the markings do not cause the trees in the plots to be treated differently from the trees outside the plots. Recording the distance and direction from the plot center to each tree is very useful in later relocating plot centers.

4.5 THE FOREST CARBON INVENTORY TEAM

A national forest inventory team should be comprised of:

- An entity with overall responsibility for the entire inventory and the ability to make decisions that are binding to regions (if regions are used). The entity may be governmental or may be part of a university or some other non-governmental organization with appropriate expertise and ability to continue operation. The national entity is responsible for planning the inventory, which includes:
    - Selecting the sampling and plot design;
    - Setting up the protocols for the collection of data;
    - Organizing the procurement of data collecting equipment;
    - Processing and analysis of data;

    - Coordinating with the land-cover mapping team; and
    - Coordinating with regions and users of inventory results.
- Regional offices that are responsible for:
    - Organizing and training the field teams;
    - Performing quality checks on the data collection performed by the field teams;
    - Providing backstopping support to the field teams;
    - Entering data (including translating local species names into scientific names); and
    - Transmitting data to the central national office.
- Field crews responsible for data collection.

A key issue is how field crews will be staffed. A well-established national inventory where measurements are repeated regularly should have its own staff. If the inventory covers a very large area, it may be efficient to have different staff in different regions. Community-based monitoring is discussed in Chapter 7; the training and incorporation of local communities should be one goal for national inventories. Ideally, field crews should be a combination of technicians with measurement skills accompanied by local inhabitants. The inclusion of local inhabitants is crucial for the following reasons:

- Allow access to the plots;
- Provide information on the local names of species measured; and
- Provide information on the uses of important species found in the plot.

Field crews will need training to apply the selected protocols of the inventory. After training, an experienced supervisor should keep in close contact with crews during their first month of work. Supervision should include visiting crews as they are doing plot work, and checking the accuracy of their measurements (quality assurance and quality control is addressed below). It is highly desirable to have locals included in the field crews, because they tend to know access routes and other locally unique information. On the other hand, the training of local inhabitants to collect forest inventory measurements may not be cost effective, especially if data collection is not performed frequently. One solution is to have teams composed of individuals who, together, capture the necessary measurement skills, species identification ability, and local knowledge. This might mean having technicians with measurement skills who travel around large areas and temporary crew members who know local terrain and assist in measurements. Community monitoring may be more practical for detecting and specifying locations of infrequent events, such as new logging or clearing.

4.6 FIELD WORK AND ANALYSIS

4.6.1 Field work

Preparation for field work requires more than writing a field protocol and choosing plot locations. Key components of successful field work are:

- Logistics planning and implementation to ensure that training, equipment, supplies, transport, food, lodging, and communications are all provided as needed;
- Field manual specifying how field work is done, and how to address unusual cases;
- Quality objectives for each measurement; and

- Field data check procedures, which may be limits on acceptable values of data entries if electronic data recorders are used, or procedures where team members check each other , as the data is being measured and recorded. Quality assurance procedures should include both immediate checks where a supervisor or another person spot checks data by re-taking measurements (while the team is still on the plot), and check cruising where a different team independently re-visits and re-measures a subset of plots, and an independent person compares the two sets of measurements to make sure that measurements are within the required accuracy and precision limits. There must be a process for giving crews feedback on the quality of their work, ideally with rewards for good quality work and additional training if deficiencies are found.

Manual instruments such as diameter tapes, tape measures, and clinometers may be easier for field technicians to learn to use, and may be more durable than electronic measuring instruments. However, using laser hypsometers is much faster than tape measures and clinometers for measuring tree heights. Laser rangefinders may be needed to estimate the heights of tall trees in dense forests. Typically, the greatest challenge in estimating costs is the number of plots per day that a field crew can measure. Often, this depends more on the amount of time it takes to get from one plot to the next than the amount of time spent at each plot.

Many projects record field data on paper data sheets. Paper data sheets are both low cost and familiar, easy for field technicians to use, and do not fail due to dead batteries or mechanical problems. Electronic data recorders can be hard to keep charged through multiday periods in the field, and data should be removed from field recorders daily which can be difficult if teams go into the forest for a week or two at a time. Electronic data recorders also require substantial skill to set up. Over time, however, data recorders can save considerable costs of printing data sheets and copying data from paper sheets to electronic form. Electronic forms can be designed to prompt users to fill in missing values and can question or reject implausible values. Tree species can also be specified using a menu, avoiding considerable time spent sorting out spelling errors in species names. While commercial timber cruising software is readily available, it may not be adaptable to record the data that an inventory needs to record.

There are a variety of textbooks and manuals available that describe how to perform field work. It is recommended that countries carefully review multiple manuals when developing their own field manual, and field test procedures before adopting them. The United States, Canada, Ecuador, Mexico, Russia, and others have detailed field manuals that provide useful examples when designing inventories.

4.6.2 Laboratory analysis of samples

Generally, laboratory analysis of woody biomass samples is not needed. Exceptions are identification of unknown tree species and determination of wood densities. For discussion of determination of wood densities, see Smith et al (2007).

Soil carbon does require laboratory analysis. Key components of soil carbon quantification are:

- Soil depth to be measured (in cm, usually 30 cm possibly 20 cm or deeper than 30 cm);
- Soil bulk density (in g/cm3); and
- Organic carbon content (percent).

The depth of sampling is specified in the inventory design. Bulk density is calculated for each sample from the measured mass and measured volume of samples. Bulk density can be measured on samples from which a subsample is later removed for carbon measurement, or from a separate sample taken at the same location as sampling for carbon. Carbon content is determined by laboratory analysis.

The most common techniques for analyzing the carbon proportion of soil are based on measurements of the emissions from the dry combustion of the samples. This approach involves oxidizing a small sample at very high temperatures and using infrared gas absorption or gas chromatography to measure the amount of carbon dioxide emitted.

4.7 CALCULATING CARBON STOCKS FROM FIELD DATA

4.7.1 Data management for calculations

Calculating carbon stocks from field data must be done in an organized manner or errors will occur. Calculation procedures should be tested on pilot data prior to committing to a particular inventory design, to ensure that all needed data will be collected. Procedures should include specifying the sequence of calculations, version tracking, limiting who can make changes to data, and tracking any changes to data. Factors used in calculations should be well documented as to their values, sources, and why the particular values are used in particular situations.

For UNFCCC reporting, it may be necessary to separately calculate the stock (or stock change) of each reported carbon pool. However, if separate reporting of each pool is not required, there is the option of calculating the carbon stock of each carbon pool on a per hectare basis, and then summing the pools to get the per hectare carbon stock represented by each plot. Having all plots on a per-hectare basis allows calculation of statistical confidence of measurements based on the variability across plots and the numbers of plots. Combining all pools is statistically appropriate and tends to give somewhat lower plot-to-plot variability than separately calculating the stock of each carbon pool. However, there is often interest in knowing the change in stocks of a particular pool—especially the live tree pool—and it is often desirable to separately calculate stocks for different pools or groups of pools. If only some pools are measured, and default Tier 1 factors are used for other pools, the non-measured pools should not be combined with the measured pools before the calculation of uncertainty.

If carbon stocks (or stock changes) are calculated separately for different pools occurring at a particular site, a statistician should be consulted to give proper methods of calculating the total uncertainty for the land type. For example, if 100 plots are measured in forest and there are live tree, dead tree, coarse woody debris, shrub, herbaceous, and litter pools, the different pools do not count as different samples when calculating uncertainty. The sample size is $n = 100$, not $n = 600$, which would be the case if each observation of each pool counted as a different sample. Methods for calculating uncertainty in simple situations are described below.

Carbon stock for a stratum is obtained by calculating the average carbon stock per hectare of all the plots within a stratum and multiplying by the area of the stratum to get the stratum carbon stock. Total carbon stock is then calculated by summing the stocks of the different strata. If the carbon stock is calculated separately for each inventory date, the change in stock is often calculated as the difference of means between the two times. If temporary plots are used, and the same plots are not measured at the two different times, difference of means must be used. Alternatively, if permanent plots are measured, the change can be calculated for each plot, and, from this, population level estimates of the total amount of change can be calculated. For a given number of plots, this approach usually gives greater statistical confidence (as long as plots with significant disturbance—such as logging or fire—are not mixed with plots without disturbance) and statistical uncertainty is calculated from the set of changes observed on the different plots. Calculation of carbon stocks from field data requires good organization to ensure that the data are efficiently sorted and the resulting calculations are correctly generated. It is important to record the details of data manipulations performed, including: corrections of errors in the data; deletions of uncorrectable data, factors and equations used, including the sources of those factors and equations; the sequence of calculations; and the reason for each calculation. Without robust records it is impossible to check the quality and accuracy of calculations and resulting carbon stock estimates, and this information is key in the subsequent verification phase of MRV.

Before calculations are begun, all data should be compiled into a single file for each carbon pool. Data should be examined for missing and implausible values. Problems should be checked against plot sheets or earlier forms of the data, and correct where possible. If correction is not possible, drop the data from the data set, recording the reason why the data was dropped. Data should not be removed from the analysis only because values are outliers.

4.7.2 Allometric equations

Application of allometric equations

Carbon equations usually take two forms: allometric equations or biomass expansion factors. Allometric equations are regressions derived from detailed measurements of volume of trees, or weighing of harvested trees and relating one or more structural variables — typically DBH and tree height — to a variable of interest, such as tree volume or biomass (Diaz and Delaney, 2011). Significant errors are likely to occur if equations are applied to trees larger than the range from which the equation was developed, and there will be no way to determine the size of the errors. As a result, biomass equations should not be used for trees larger than the largest tree used to develop the equation in question, unless the biomass estimates for these larger trees are compared to measured biomass of other large trees and the estimates are documented to be reasonable. Alternatively, equations for a similar species may be used, and adjusted for the difference in wood density.

Most allometric equations give very unrealistic results when applied to trees larger than the trees from which the equation was developed. Therefore, it is preferable to use allometric equations that are developed from trees similar to those being studied. In particular, the species or growth form and potential biomass should be similar. This unreliability is particularly great with equations that are simple exponential models. Logistic equations, where the rate of increase in predicted biomass declines as the diameter gets large, tend to have less error when applied to trees larger than the trees from which the equation was developed. Unless the allometric equation was developed using measurements of trees in the area where the equation will be used, and from stands with similar trajectories of development as the stands to which the equation will be applied, equations that use diameter only should be considered useful for rough estimates of biomass only. General equations are provided in Annex 4A.2 of the IPCC Guidelines. If an equation will be applied to a wide variety of species, either the species should be grouped so that each group has a similar wood density, or wood density should be incorporated into the biomass estimation.

Equations that use height and diameter but not wood density can be adapted to estimate the biomass of species different from the species from which the equation was developed, if the growth forms of the species are all similar, and if estimates are adjusted for differences in wood densities. In this case the wood-density adjustment factor is calculated by dividing the specific gravity of the species to which the equation will be applied by the specific gravity of the species used to develop the equation.

BCEFs are dimensionless factors that convert the merchantable volume of trees into their aboveground biomass. BCEFs are used for rough estimates of biomass when a timber inventory is available but resources are not available to measure carbon stocks in forests. They are unreliable when applied to forests of different structure from the forest where the BCEF was developed. Having species utilization standards, a different disturbance history, different forest management practices, different logging history, or different stand age is likely to cause a BCEF to give an inaccurate biomass estimate. Various sources can be useful when seeking allometric equations and BCEFs, such as local forestry institutions, the library of the Center for Tropical Agricultural Research and Training and published literature (e.g. Chave et al, 2005).

Developing new and testing existing equations

If no information is found regarding a certain species or group of species[8], REDD+ projects may have to develop new allometric equations. Under the Global Environmental Facility's (GEF) Carbon Benefit Project, Dietz and Kuyah (2011) have prepared Guidelines for establishing regional allometric equations through destructive sampling.[9] Another guide for developing allometric equations is Aldred and Alemdag (1988).[10]

Developing new allometric equations can be done with a relatively small sampling of approximately 30 trees for a particular species or group of species, but a larger sample is desirable. Wood density may have to be measured. Because forest measurements are made on live, green trees, green wood volumes must be used to calculate wood density, not dry wood volume.

Checking the fit of published allometric equations is good practice when equations are applied to sites with different productivities, climate conditions, or growing conditions from where the equations were developed. This can be checked by destructive sampling or measuring the volumes of a few trees of different sizes. Destructive sampling is cutting down and weighing a few trees, and cutting a small subsample of tree parts, weighing them in the field and then drying them to develop a dry to field weight ratio for the weights of the whole trees. Volume is measured by dividing the tree trunk into segments and measuring the two end diameters and the length of each segment, and also taking measurements on a sample of branches.

Belowground biomass

Belowground biomass is extremely difficult to measure for an individual tree, because roots of different trees and shrubs intertwine. As a result, belowground biomass is often estimated using general equations that estimate it as a function of aboveground biomass. The IPCC approves the use of equations from Cairns et al (1997). In general, the ratio of belowground biomass to aboveground biomass is higher on sites with less above ground biomass than dry sites. For large projects on dry sites, it may be worth doing destructive sampling to measure the biomass of roots in the project area, because these measurements may give significantly greater biomass than default ratios for sites of any productivity. Belowground biomass can be measured by digging and weighing root balls, and coring a sample of locations between the stems. Methods are described in Bledsoe et al (1999).

4.7.3 Non-tree pools

Scaling up from samples to a per-hectare mass is straight-forward. Samples are dried and weighed and the dry to field weight ratio is calculated. The field measurements are transformed to dry weight and scaled to per hectare basis.

Processing of litter samples and calculations of litter biomass are similar to the methods used for herbaceous vegetation. The carbon proportion of dry biomass weight can be estimated either by laboratory analysis, or by examining samples to see what plant parts compose the litter (e.g., foliage versus branch wood, stem wood, or dead herbaceous vegetation), finding the carbon contents of each component in the literature, and calculating a weighted average carbon fraction.

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[8] The most useful groupings may be by morphology class (e.g., single-stemmed trees, multiple-stemmed trees, shrubs) (MacDicken, 1997).

[9] Another guidance to develop biomass tables is found on MacDicken (1997) Annex 4, Section C.

[10] Aldred, A.H. and I.S. Alemdag. 1988. *Guidelines for Forest Biomass Inventory.* Information Report PI-X-77. Canadian Forestry Service, Petawawa National Forestry Institute. 134 pp.

The volume of coarse woody debris per hectare is calculated for each density class for each stratum:

$$\text{Volume of coarse wood debris (m3/m2)} = \pi 2 * [(d12 + d22 + \ldots + dn2)/8L]$$

where d1, d2, dn = diameter (m) of each of the n pieces intersecting the line, and L = the length of the line (100 m; Harmon and Sexton, 1996). Volume is converted to mass using the appropriate density factor.

4.7.4 Combining carbon pools

The per-hectare carbon stock of each pool in each plot is summed with the other pools in that plot to give the per hectare carbon stock for each plot. The total carbon stock is calculated by multiplying the average value per hectare times the number of hectares.

In reality, measurements will be taken over a period of weeks to months. However, for the sake of reporting and change over time, measurements are taken as representing a particular date. Some inventories only specify the year that measurements represent. However, because some carbon stocks vary between seasons, it is better to assign a date that the measurements represent. For example, measurements taken during a dry season of November 2011 through February 2012 could be taken to represent the carbon stock present as of February 1 of 2012. If inventories are taken over multiple years, either a panel design should be used to calculate the average and changes, or models should be used to normalize the data to a single year. These methods are beyond the scope of this manual. Consult an appropriate textbook for guidance on how to use these methods.

4.7.5 Quantifying uncertainty

The reliability of carbon stock estimates is reported in the form of statistical confidence intervals that quantify the chance that the sample plots used to calculate carbon stocks might be different from the actual conditions that exist throughout the entire forest.

A common index of uncertainty associated with an estimate from an inventory is the confidence interval. The confidence interval represents a range of values surrounding an estimate, typically the mean—that is, most likely. The width of the confidence interval conveys to the data consumer a sense of confidence in the accuracy of the estimate. Confidence intervals can be calculated for different "confidence levels", and are based on statistical theory. Typical confidence levels are 90 percent and 95 percent. To interpret, for example, a 95 percent confidence interval of +/- 10 percent surrounding an estimate of 100 tons per hectare of carbon, one can say that if a similar inventory was conducted many times in the exact same way but choosing a different set of plots, 95 percent of the confidence intervals generated would contain the true population value. The true population value is the value that would be found if every individual in the population was measured. In this example, the population value would be the carbon stock measured if every tree was measured. People often interpret that to mean that one can be 95 percent confident that the true value lies within the confidence interval, in this example, between 90 and 110 tons per hectare.

Technically these uncertainties are reporting the chance that the sample is different from the actual total population. The technical name for this chance difference is sampling error. There are many other kinds of errors that could lead to false numbers. There are several mechanisms that can be used to limit errors other than sampling errors. These include quality standards, and independent checking of measurements, data, and calculations to detect and fix human errors. All these potential errors mean that two independent measurements of the same tree, made by different people, might differ by a few millimeters. Nonetheless, most assume that these non-sampling errors are random and not biased, and thus that they increase the confidence interval and do not bias the stock estimates.

To calculate a confidence interval, first the standard deviation and standard error of the estimate must be calculated. The standard deviation is a measurement of how different individual samples are from each other.

For example if the standard deviation of a set of plots is 50 tons per hectare of carbon, then approximately 2/3 of the plots will have carbon stocks within 50 tons per hectare of the average carbon stock. The standard deviation is a property of the population. The standard error of the estimate is a measurement of uncertainty of the estimate of the mean value. The standard error is a property of the sample and can be reduced by measuring a larger sample, i.e., measuring more plots. The standard error of the estimated mean for each carbon pool within each stratum is:

$$SE = \sqrt{(S/n)}$$

where SE is the standard error of the estimated mean carbon stock per hectare for the particular carbon pool and stratum; S is the standard deviation of the estimated mean carbon stock per hectare of the particular carbon pool and stratum; and n is the number of plots in the stratum. The confidence interval for each carbon pool within each stratum is then calculated. The confidence interval is:

$$CI = \pm t \times SE$$

where CI is the confidence interval; t is the $t_{critical}$ point from a table of student t test values, for the appropriate confidence level and degrees of freedom. This is for a two-tailed test, i.e., a 95 percent confidence would leave 0.025 of the probability in each tail of the distribution, and the degrees of freedom is typically the number of plots minus one. SE is the standard error for the particular stratum and pool.

The confidence interval can be expressed as a percentage of the mean:

$$U_n = (CI/\overline{X})$$

where: U_n is the uncertainty in percent for pool and stratum n; CI is the confidence interval for that pool and stratum, in tons per hectare; and $\overline{X}$ is the average estimated carbon stock of that pool and stratum, in tons per hectare.

There are multiple acceptable methods for combining uncertainties across multiple pools or strata. The methods differ depending on the degree of difference of type between the pools or strata, and the degree of congruence of sampling methods used in the different pools or strata. Pools should be independent. Technically, pools should be spatially separated. For example, on-site biomass and carbon stored in wood products are separate pools. Separate classes of biomass, such as live trees and dead trees, should be combined to estimate the biomass carbon stock.

If the inventory is stratified, the uncertainty is reduced relative to the same number of plots in a simple random sample. To calculate the uncertainty of a stratified inventory, the uncertainty is calculated for each stratum then the uncertainties are weighted and combined. The details of calculating the uncertainty of a stratified inventory are beyond the scope of this manual. For guidance, consult a forest measurement textbook such as Avery and Burkhart (1994) or a statistics textbook. Note that typical uncertainties in forest inventories are generally weighted by the number of sample units observed in each stratum or by area, rather than by the number of tons in each stratum. Also, if doing paired sampling, consult a statistics textbook for guidance.

4.7.6 Quantifying uncertainty in periodic emissions or sinks

If calculating the change in carbon stock from one simple random sample to another simple random sample measured at a later date, the change is calculated as the difference of means. Methods for calculating the confidence of a difference of means are presented in many statistics textbooks.

If the uncertainty for a combined estimate of sinks or emissions from multiple, independent pools is being calculated, particularly if different pools are measured with different UNFCCC methodology tiers (such as

Tier 1 factors for shrubs and forest floor, and Tier 3 measurements of live trees) the combined uncertainty of the estimated change can be calculated using Equation 5.2.2 from the UNFCC "Good Practice Guidance for LULUCF" (2003):

$$U_E = \sqrt{\frac{(U_1 + E_1)^2 + (U_2 + E_2)^2 + \cdots + (U_n + E_n)^2}{|E_1 + E_2 + \cdots + E_n|}}$$

where UE is the combined uncertainty in percent for the sum of changes in all pools 1 to n, in tons in the entire group of pools; Un is the uncertainty in percent for pool n; and En is the emission or removal for the stratum, for the pool n, in tons in the entire pool. Some people argue that to comply with the principle of conservativeness, when using IPCC default values it is advisable to use the lower estimate (subtract the error to the mean value) when calculating the existing or increasing carbon stocks and the upper estimate (add the error to the mean value) when calculating emissions. However, if multiple factors are multiplied, using a very conservative value for each factor gives an improbably low estimate of sinks or improbably high estimate of emissions. If there is no reason to think that the area or emissions are different from the instances used to develop the factors, then it is probably more reliable to make calculations using the most likely values and report the uncertainty range, even though the uncertainty range could be greater than the estimated magnitude of the sink or source.

4.8 DATA CHECKING AND REPORTING

4.8.1 Data cleaning, checking and accuracy standards

Data quality is essential. If field data have substantial errors, the entire inventory could be worthless. Inventory design, field technician training, and management of field crews are the foundations of data quality. Regardless of the strength of the foundation, data must be thoroughly checked before carbon stocks are calculated. This includes checking for missing data and implausible data values. As discussed above, if no reliable correction of a data error can be achieved, the faulty plot should be excluded from carbon stock calculations.

4.8.2 Archiving data and metadata

To be able to calculate changes in carbon stocks over time, data from an inventory must be stored in such a way that it can be retrieved later, to recalculate change in carbon stocks over time. Methods for measurement, data cleaning, and any adjustments or calculations must be clearly specified to allow later users to be confident that later measurements and calculations are comparable to earlier data.

Metadata describe how data are collected and what they represent. Key aspects of forest inventory metadata are the protocols used to direct field crews in their work. Often little attention is given to archiving data and metadata. Ideally, professional data managers will be consulted in the design of data storage forms and use of data storage equipment. At a minimum, it is important to have a plan for how data and metadata will be stored and protected from unauthorized changes or loss. Data should be archived in at least two locations. Information about where data is stored, what is included, and who controls access should be readily available. Having teams of people working on data analysis maintains awareness of the data, and their access and appropriate uses. Relatively frequent use of the data ensures that data will be transferred to new storage and retrieval media or formats, as new equipment and software are adopted.

4.8.3 Data analysis and reports

Typical reports from forest carbon inventories include:

- Calculations of biomass and carbon stocks, often with reports by pool and stratum;
- Calculations of stock changes over time;
- Timber inventories, or at least estimates of wood volume in live trees; and
- Reporting uncertainties, across pools and strata.

Over time, forest inventories become irreplaceable windows to the past. The initial use of an inventory might be only to measure timber volume or carbon stock, or to be the start of the estimation of changes in carbon stocks. Depending on parameters measured, they may contribute to the study of additional dynamics as well. However, as repeated measurements form an archive, the value of these data will increase. New needs and questions arise, and a well-documented historic data set can provide a window into past conditions or changes, and provide a way of seeing into the past and evaluating changes over time without having to wait years or decades for a new set of measurements. One cannot foresee what issues will become important in the future, and past experiences shows that a well-maintained inventory will likely have many valuable uses.

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5.0 REMOTE SENSING OF LAND COVER CHANGE

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5.1 INTRODUCTION

This chapter focuses on the application of remote sensing-based approaches to forest cover and change monitoring. Remote sensing provides the most practical option for monitoring land cover change over large areas. This chapter emphasizes optical satellite remote sensing of deforestation. Optical satellite remote sensing is the most heavily used type of remote sensing for this application, and deforestation represents the largest source of greenhouse gas (GHG) emissions from the land-use sector in most tropical-forest countries. Another important use of remote sensing in a Measurement, Reporting and Verification (MRV) system is to produce a forest benchmark map. This is needed to define the national forest area at the beginning of a reporting period and within which carbon stocks and forest changes will be monitored. Finally, remotely sensed data represent a key input to the stratification of forest types as variables, such as seasonality of leaf cover, inundation, and spectral variations due to very different canopy structures can be extracted from these data and, thus, inform the forest stratification. At a minimum, this stratification includes the identification of forest types with potentially significant differences in biomass levels that should be considered in field sampling (see Chapter 4). Additional forest strata could be of interest for national management and planning purposes and such stratification activities can be facilitated through the use of remotely sensed data.

The Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF) is a key resource for countries. However, it provides limited information on specific approaches to remote sensing of land use. The information in this chapter summarizes remote sensing issues for national MRV systems. Other valuable resources include the MRV Guidelines produced by the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) group, the United Nations REDD+ Programme (UN-REDD) National Forest Monitoring Systems document (UN-REDD 2012), and the REDD-plus CookBook (Hirata et al, 2012). Links to additional resources for training on remote sensing are provided in Section 5.8.

This chapter discusses:

- The context of land uses within the United Nations Framework Convention on Climate Change (UNFCCC)
- A review of remote sensing
- Overall steps and needs for consideration in developing a monitoring system
- An overview of emerging areas of remote sensing-based research for forest monitoring

5.2 LAND USES AND CATEGORIES IN THE UNFCCC

LULUCF within the context of the United Nations Framework Convention on Climate Change (UNFCCC) refers to land-use change or persistence among the six broad uses defined by the IPCC: Forest Land,

Cropland, Grassland, Wetlands, Settlements, and Other Land (IPCC 2006, Vol. 4; see Chapter 2). Possible types of land-use change among, or persistence within, these six broad uses are called Categories. Sub-categories can be defined within a category to more precisely define changes and emission sources. Activity data (AD) are data on the area of a Category that potentially results in GHG emissions or removals, over a given period of time. As illustrated in Chapter 3 (Figure 3.2), AD are combined with data on differences in the carbon stocks before and after the cover change has occurred, called Emissions Factors (EFs), to estimate the associated GHG emissions for each category.

The IPCC (2006) describes three overall approaches, not to be confused with tiers, for the representation of land use (see Chapter 3). These approaches are used to estimate AD for each Category:

- Approach 1 is based on estimating the total area of each land-use category without tracking of changes among categories
- Approach 2 includes the tracking of specific changes, or persistence, between land-use categories over time
- Approach 3 builds on Approach 2 as it includes the spatially-explicit tracking of changes between categories, presumably via monitoring with satellite imagery.

Approach 3 is most informative and applicable to a mechanism for reducing emissions from deforestation and forest degradation (REDD+). However, it is acceptable to use a mix of the three approaches among regions or categories in a country. Case studies of countries that have used different approaches are provided in Annex 2A.1 of the GPG-LULUCF. For example, existing data available for the Argentine Pampas were sufficient for either Approach 1 or 2. Agricultural census data, documenting the area of each land use over time and with full coverage, existed for the entire region, thus enabling Approach 1. Data on land-cover change, documenting transformations between natural grasslands to pasture and cropland existed, thus enabling Approach 2. In Australia, the creation of a multi-temporal map of change in forest cover as well as some sub-categories enabled Approach 3 for those categories.

It is important to consider the characteristics of land-use parameters that will be monitored and the cost implications of a full-coverage mapping versus a sampling-based method. While satellite-based remote sensing is a valuable tool for monitoring several parameters of land use, some types of land-use categories (e.g., forest degradation), or regions (e.g., mountainous areas), may be more effectively monitored through airborne or ground-based data collection approaches. The costs associated with these approaches could be significant and thus necessitate a sampling-based approach.

5.2.1 Definition of national forest and other classes

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories consolidated LULUCF and Agriculture into the Agriculture, Forestry, and Other Land Use (AFOLU) in Volume 4 (IPCC 2006; See Chapter 3). Throughout this chapter, definitions have been adapted from the 2006 IPCC Guidelines and the GPG-LULUCF 2003, unless noted otherwise. While countries must report on land use, satellite monitoring is more suited to detecting land cover, as it is based on relationships between observed spectra in the images and the structural characteristics of the soil and vegetation covering land. Land use, however, can usually be inferred based on local context and a general knowledge of the area.

Forest definition

A fundamental step in the development of a MRV system is the national definition of forest. Countries have some flexibility in developing their forest definition, yet they are constrained by certain criteria. The definition must be developed based on both the physical structure of the present and potential vegetation as well as how the land is used. The physical criteria for forest, and the range that countries can select for their definition are:

- Potential to reach a minimum canopy height at maturity of 2m to 5m;
- Minimum tree-crown cover of 10 percent to 30 percent; and
- Minimum patch size of 0.05 ha to 1 ha.

Tree-crown cover is not the same as leaf cover, as tree crown cover is defined by the periphery of the crown. A site is defined as forest if it meets the above criteria *and* if its main use is assumed to be forest-related. For example, while an urban park or agricultural fallow may meet the physical criteria of forest, these areas have urban and agricultural uses (i.e., non-forest uses and), thus, they belong to a non-forest category. Agricultural fallow is a particularly important example for many tropical countries, as much of their agricultural land is in some stage of fallow. While in terms of structurally these are young, regrowing "forests," they are part of an agricultural cycle with a defined temporal period, and are expected to be re-cleared after that period. Therefore, they are part of a non-forest use. Considering agricultural fallows as non-forest greatly facilitates reporting on deforestation and associated GHG emissions, since a country would not be required to estimate rates of the appearance of new fallows and their re-clearance when reporting changes in forest area. A full list of each country's national forest definition is available at http://cdm.unfccc.int/DNA/index.html.

According to the IPCC Report *Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types*, forest degradation could be defined "a direct human-induced long-term loss (persisting for X years or more) of at least Y percent of forest carbon stocks [and forest values] since time T and not qualifying as deforestation or an elected activity under Article 3.4 of the Kyoto Protocol" (IPCC 2003). For example, selective logging may occur in a site defined as forest. If the tree cover was not reduced enough to pass the threshold of the forest definition, then the site remains forest, yet has undergone degradation. Conversely, another site that has been logged and did cross this threshold could be classified as deforestation. However, in addition to the change in physical structure, the use of the land must also change. If the site is still under a forest use, i.e., forest concession subjected to some selective-logging cycle, it would still be defined as forest despite the structural change. In this case, there are carbon stock losses in the 'forest remaining forest' class. This will likely necessitate a subclass for 'intact to degraded forest,' and this subclass should be sampled to estimate carbon stock change.

Other classes

It may be important to further stratify the six broad use classes where carbon stocks vary significantly, and this should be assessed as part of both the national Key Category Analysis (KCA), outlined in section 5.3, and the forest stratification process discussed in Chapter 4. Including additional classes may provide data that are very useful for REDD+ national strategies and management policies. Tables 5.1 and 5.2 show examples of a land-cover change matrix with three broad categories compared versus one with greater thematic precision. However, there is usually a trade-off between thematic precision of a land-use change study and the accuracy of the change estimates (e.g. Mather 1999; Foody 2000). Countries should have strong justification for including additional classes as key categories for monitoring, in terms of the expected increase in the accuracy of emissions estimates and overall usefulness of the monitoring system versus the cost of this additional detail.

Issues related to sub-classes are somewhat different for forest versus non-forest. For forests, a country will conduct a stratification for a national forest inventory. This may involve the use of ancillary data, such as on elevation and climate as well as spectral data for sub-classes that have very different structural attributes that yield distinctive spectra, such as palm forest and liana forest. This would be done just once for the benchmark map, as one can assume there are no transitions among these naturally-occurring vegetation types over the required reporting periods.

In contrast, transitions among different post-deforestation land uses do occur over short time periods. Spectral distinction of these uses is often difficult, especially when one cannot be very selective about the season of the imagery used for analysis because of frequent cloud cover. For example, managed grassland, cropland, plantations and fallows may be difficult to distinguish, depending on the season and stage of crop

development at the acquisition times of available images. Again, strong justification in terms of improvement of emissions estimates is needed to justify attempts to include transitions among these classes.

A step-wise process may be worth exploring that uses different methods and levels of detail for different aspects of the monitoring needs. For example, an initial step could be to produce a forest benchmark map, with forest sub-classes that have significantly different carbon stocks. A second step could be to produce a map of a single, broad deforestation class that occurs anywhere within this benchmark. By combining the two, deforestation can be attributed to different forest sub-classes. A third step could be to use samples of airborne or other very-high resolution data to estimate the proportions of sub-classes of non-forest following deforestation, as well as any important transitions among those.

Combining approaches like these can provide all of the necessary estimates to complete a full land-cover change matrix, while not requiring a very difficult process of spectral classification of all transitions among sub-classes. This is an area where there are many options, and many different opinions within the research community.

Table 5.1: Example of a land-use change matrix with few land-use classes and change categories. "Forest" in this table is non-degraded forest only. "Non-forest" includes all non-forest, both naturally-occurring and anthropogenic. Values in (a) are in absolute units, such as hectares, and in (b) are percentages. T1 and T2 are the first and second time periods, referred to in the IPCC as "Initial land-use class" and "Land use during reporting year." Values in Sum T1 and Sum T2 are total area and percent change for each class. Values inside the matrix are areas and percent change for each category of persistence or change. In this example, gross deforestation plus forest degradation is 0.6 percent (adding values 0.4 and 0.2 in the first row of (b)).

T2

	a)	Forest	Degraded Forest	Non-forest	Sum T1
	Forest	9,940	40	20	10,000
T1	Degraded Forest	5	1,970	25	2,000
	Non-forest			4,000	4,000
	Sum T2	9,945	2,010	4,045	

	b)	Forest	Degraded Forest	Non-forest	% T1
	Forest	99.4	0.4	0.2	100
T1	Degraded Forest	0.3	98.5	1.3	100
	Non-forest			100.0	100
	% T2	99.7	98.9	101.5	

Table 5.2: Example of a land-use change matrix with more precise land-use classes and change categories. "Forest" here means intact, non-degraded forest, according to the national forest definition. Natural Grassland, Fallow, Cropland, and Pasture represent non-forest classes. Values in (a) are in absolute units, such as hectares and in (b) are in percent. T1 and T2 are the first and second time periods, referred to in the IPCC as "Initial land-use class" and "Land use during reporting year." Values in Sum T2 are total area and percent change for each class. Values inside the matrix are areas and percent change for each type of category. In this example, the majority of forest occurs in the lowlands, the majority of deforestation (to fallow, croplands, and pasture) and forest degradation also occurs in the lowlands. A high degree of rotational land use is also indicated by, for example, the large areas of change from cropland to fallow (200) or pasture (100). The 12.5 percent reduction in fallow indicates intensification of land use, either via a shortening of fallow cycles or an increase in permanent pasture. The 35.1 percent increase in pasture indicates an increasing importance of this use.

a)

T1 \ T2	Lowland Forest	Montane Forest	Degraded Lowland Forest	Degraded Montane Forest	Natural Grassland	Fallow	Cropland	Pasture	Sum T1
Lowland Forest	7945		35			3	5	7	7995
Montane Forest		1995		5		2	3		2005
Degraded Lowland Forest	5		1500			2	6	12	1525
Degraded Montane Forest				470		1	4		475
Natural Grassland					993		3	4	1000
Fallow						350	50	150	550
Cropland						200	700	100	1000
Pasture						50		1400	1450
Sum T2	7950	1995	1535	475	993	608	771	1673	

b)

T1 \ T2	Lowland Forest	Montane Forest	Degraded Lowland Forest	Degraded Montane Forest	Natural Grassland	Fallow	Cropland	Pasture	% T1
Lowland Forest	99.4		0.4				0.1	0.1	100
Montane Forest		99.5		0.2		0.1	0.1		100
Degraded Lowland Forest	0.3		98.4			0.1	0.4	0.8	100
Degraded Montane Forest				98.9		0.2	0.8		100
Natural Grassland					99.3	0.0	0.3	0.4	100
Fallow						63.6	9.1	27.3	100
Cropland						20.0	70.0	10.0	100
Pasture						3.4		96.6	100
% T2	99.7	99.5	98.8	99.2	99.3	87.5	80.8	135.1	

5.3 OVERALL STEPS AND NEEDS

Figure 5.1 illustrates the key decisions a country must consider during the development of an effective and efficient land-cover and land-use change monitoring system. A country must first decide what categories are the most important to monitor and, based on this, the scale at which these categories should be monitored as well as how classes within these categories should be defined and monitored. A country must then consider a range of broad technical criteria for monitoring,. This includes the type and resolution of source data and the degree to which a full coverage, or sampling-based, approach should be applied to some, or all, of the land cover classes to be monitored. The appropriateness of different monitoring methodologies will need to be assessed, including the types and availability of different satellite data, pre-processing, classification algorithms, the possible level of automation, and analyst expertise. Where automation is not possible, it is important to consider how consistency will be achieved and what methods will be used to effectively combine data from different time periods.

1) What categories are most important to monitor

KCA involves identifying the major land-use-based sources of GHG emissions. This should be done as part of the development of a REDD+ strategy within the national development-planning context. For MRV, the process should extend to defining the types of land-cover changes that are major GHG contributors and to aligning these definitions with the land-cover change categories defined by the IPCC GPG. Finally, a country must determine the geographical extent where these changes are believed to occur, and thus where monitoring should be conducted. Some countries may not need to monitor their entire land area in order to estimate the great majority of national land-use GHG emissions.

2) What are the appropriate scales and/or sampling approaches for monitoring?

Once the categories and classes to monitor have been assessed, it is necessary to consider the appropriate scale and approach for monitoring the changes. For example, do change events occur in small patches of several hectares, or are they much larger? Different types of changes may also be most appropriately monitored with different sources of data. For example, some land-use dynamics may be very appropriate for satellite-based monitoring, whereas other dynamics, particularly some forms of degradation and post-deforestation land-use changes, may require airborne or field–based monitoring. These more costly data-collection processes encourage a sampling approach. Some vegetation types, such as deciduous woodland, may require data from particular or multiple seasons within each year, resulting in increased data and analysis demands.

3) What methodological aspects should be considered?

A country should consider a range of methodological options to avoid. This will allow a country to avoid, on the one hand, methods with little justification based on in-country testing or, on the other hand, spending too much time investigating issues that can be well-informed by existing literature or may be of relatively little significance to the potential accuracy of the final emissions estimates. Many differing views exist regarding the optimal methods for monitoring land-use change and, therefore, a country should seek its own cadre of experts with strong fundamental backgrounds in remote sensing to know how to access and understand the relevant literature and options. A country should obtain opinions from a range of international experts, and conduct assessments with national data, focusing on the categories identified in the KCA.

Some of the main questions are:

1) What types of satellite data are most appropriate for monitoring the classes identified?

2) What type of classification approach should be used?

3) What types of pre-processing are needed for the particular method of image analysis being considered, and what level of analyst expertise is required?

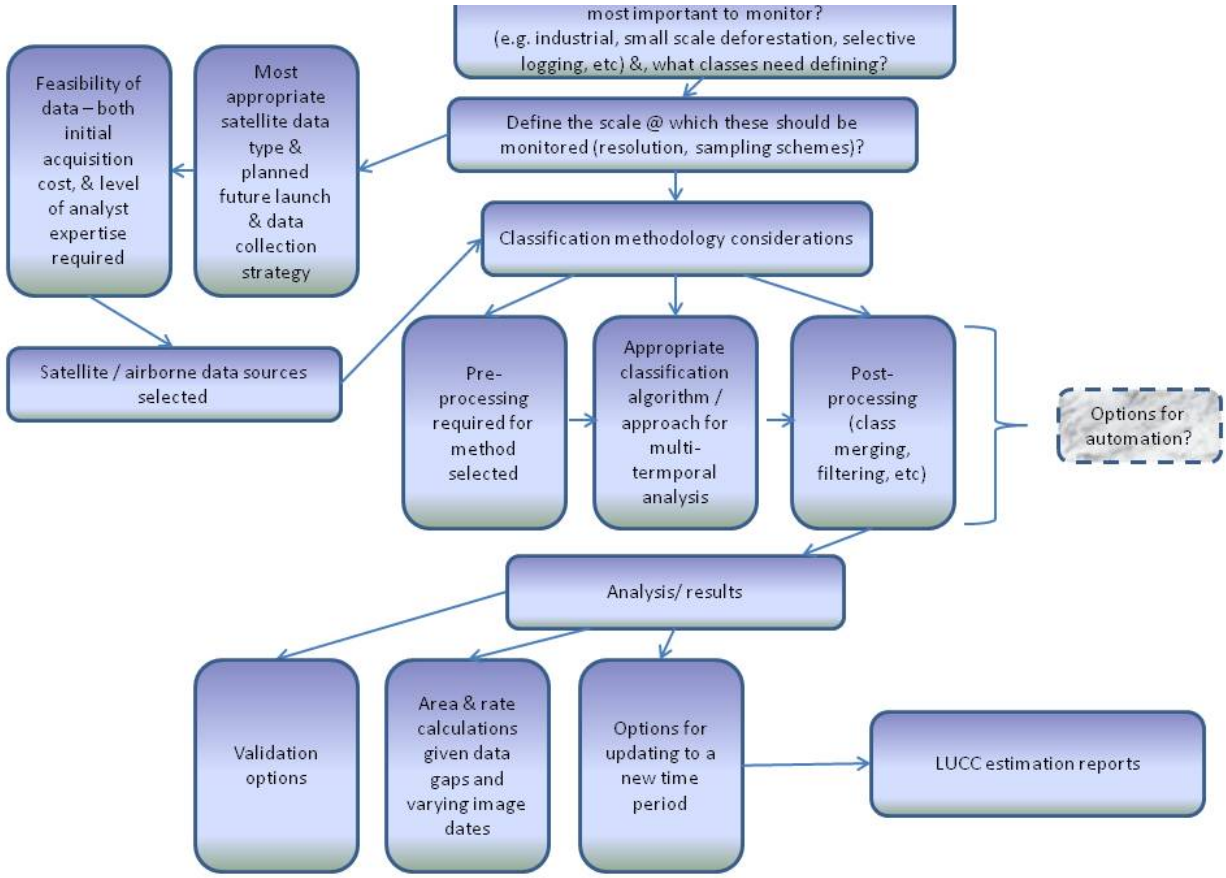
4) How much of the process can be automated, and for those parts that are dependent on analyst interaction, how can consistency and reliability be assured?

5) How should data from different time periods be combined to produce change estimates?

6) What post-classification processing steps should be applied?

7) What validation approach should be used, including data sources and sampling?

Figure 5.1: Key considerations in the development of a forest monitoring system



Some of the most important considerations are whether to use optical versus Radio Detection and Ranging (RADAR) data, what spatial resolution is needed, and whether the data source has an appropriate archive and acquisition strategy.

On question 4, a country should seek to produce the most accurate estimates possible for key categories while using an approach that is "replicable." This is a fundamental requirement of the IPCC GPG-LULUCF, although it is only vaguely defined in the context of satellite monitoring. Question 5 includes both the approach to processing the satellite imagery from multiple dates as well as the approach to estimating change rates from completed land-use change maps or sample estimates.

A country must also consider an initial process to produce a forest benchmark or baseline and a map of forest and forest types. The generation of a forest benchmark map represents a key activity in a forest monitoring system. This product provides the basis for the initial cover extent, the area within which deforestation will be mapped and the extent continually eroded. As this product provides the basis for accurately mapping deforestation, it is important to generate a robust product that has as few gaps or other artifacts as possible. Gaps, for example, can result from multiple sources including the presence of clouds in images and sensor malfunctions, such as the Scan Line Correction hardware failure of the ETM+ sensor that occurred in May 2003.

By distinguishing mature forest versus fallow areas in the first step, i.e., during creation of the forest benchmark map, a country can minimize confusion between mature forest clearing and fallow cycles in later monitoring. While older secondary forest can be difficult to distinguish from mature forest, most fallows younger than 10 years are distinguishable, and the great majority of fallow periods are shorter than 10 years. Question 6 includes merging of temporary sub-classes, possibly combining information from multiple dates into a single multi-date product, and often some type of filtering to a defined minimum-mapping unit (MMU). The MMU should be smaller than the minimum patch size in the national forest definition or, if not, a case should be made that using a larger MMU does not significantly affect resulting area estimates. However, while using a larger MMU probably does not significantly affect area estimates for static areas of classes, estimates of change can be very sensitive to the MMU. Question 7 should consider various sampling schemes and the availability of very high-resolution satellite or aerial observations, as well as an independent team of analysts to interpret the validation data and conduct the error calculations.

5.4 REMOTE SENSING OVERVIEW

This section provides a summary of remote sensing fundamentals. Numerous text books are also available on remote sensing of land-cover. Links to selected internet resources are provided in Appendix 5B.

5.4.1 Types and characteristics of remote sensing data

Remote sensing is the process of sensing energy emitted or reflected at some wavelength along the electromagnetic (EM) spectrum by some object rather than being in direct contact with it. The human eye, for example, senses a relatively small portion of the total spectrum of energy emitted by the sun; this is the visible portion of the EM spectrum. The amount and type of energy sensed is usually recorded in digital form; the amount representing the strength of the signal, and the type representing the recording of the signal across a spectrum. Fundamental assumptions, though not always valid, are that different land-cover types can be distinguished based on this recorded information and that land use can be inferred from land cover.

Satellite-based remote sensing is most common because of the full, repeated coverage offered by one or more satellite data sources; thus enabling national monitoring for terrestrial-based applications. Airborne remote sensing capacities are also of interest, as such systems could be applied over large regions, or entire countries, depending on the type of equipment, sampling approach, and resources available. At the highest level, two broad types of remote sensing for monitoring land-cover exist: passive and active.

Passive remote sensing

The majority of remotely-sensed data used for monitoring land use is passive. Passive remotely-sensed data are acquired by a sensor that passively receives energy originating from another source: the instrument does not emit its own signal. The sun is the source for visible and shortwave-infrared spectral regions or the earth or feature itself for thermal-infrared regions (Figure 5.2). The portion of the sun's energy across these spectral regions that is reflected by the land surface is often indicative of the structural and chemical characteristics of the surface features (Figure 5.3).The different spectral regions are represented by relatively narrow "spectral

bands" (Figure 5.4) and, by combining images of energy measured in different spectral bands and assigning a separate color for display, "multi-spectral" images are produced, as illustrated in Figure 5.5.

Figure 5.2: Optical satellite remote sensing. Shortwave energy is emitted by the sun, passes through the atmosphere, reflects off a surface, passes again through the atmosphere and reaches a sensor on board a satellite. The signal detected is dependent not only on the reflectance properties of the surface but also on the sun angle, topography, view angle and atmospheric properties.

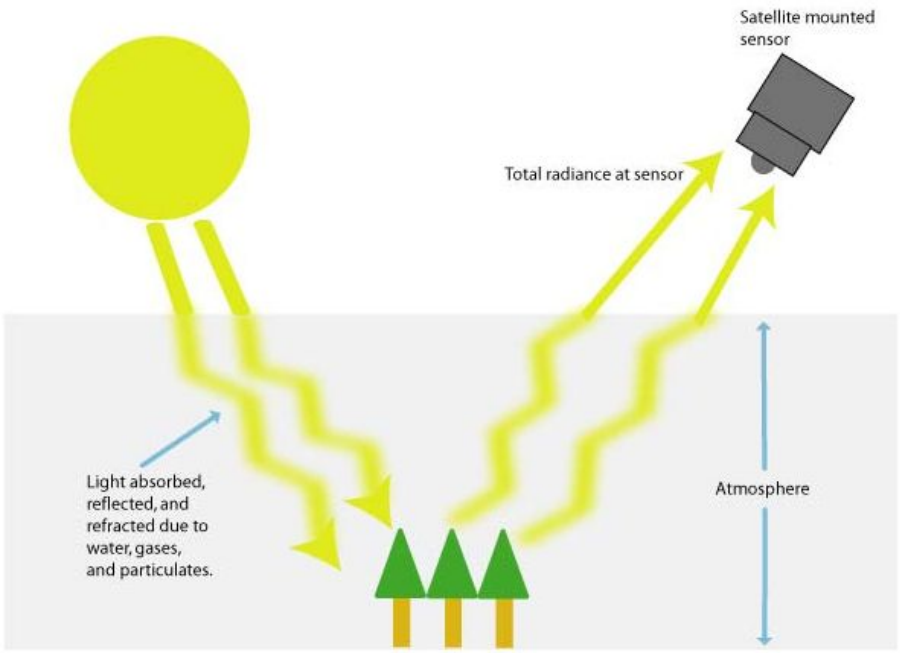


Figure 5.3: Generalized spectral curves of fundamental features in remote sensing of land-cover. Most types of land-cover are a mixture of these features, plus non-green vegetation and shadows caused by the geometry of terrain and vegetation.

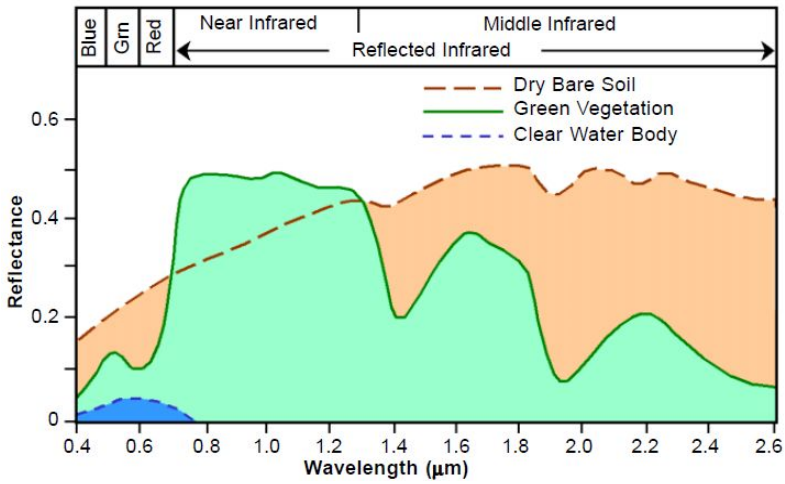


Figure 5.4: Example of spectral resolution. Both (a) and (b) represent the entire visible range of the electromagnetic spectrum. Spectral bands are defined by a range of wavelengths, and in the example here they are divided by white lines. A single channel of a multi-spectral sensor is sensitive to energy only within a certain band. In (a) the bands cover a wide range of energy, and a sensor with such bands would be considered a broad-band sensor. In (b) the bands are narrow, and a sensor with channels along these bands would have a high spectral resolution. A sensor, such as illustrated in (b), with so many channels and bands would be considered hyper-spectral.

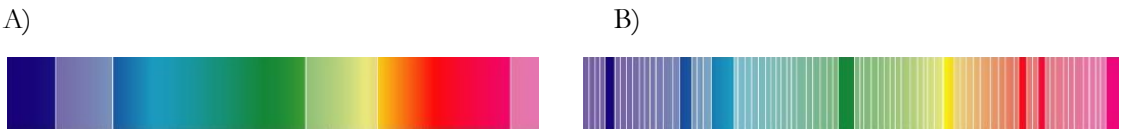
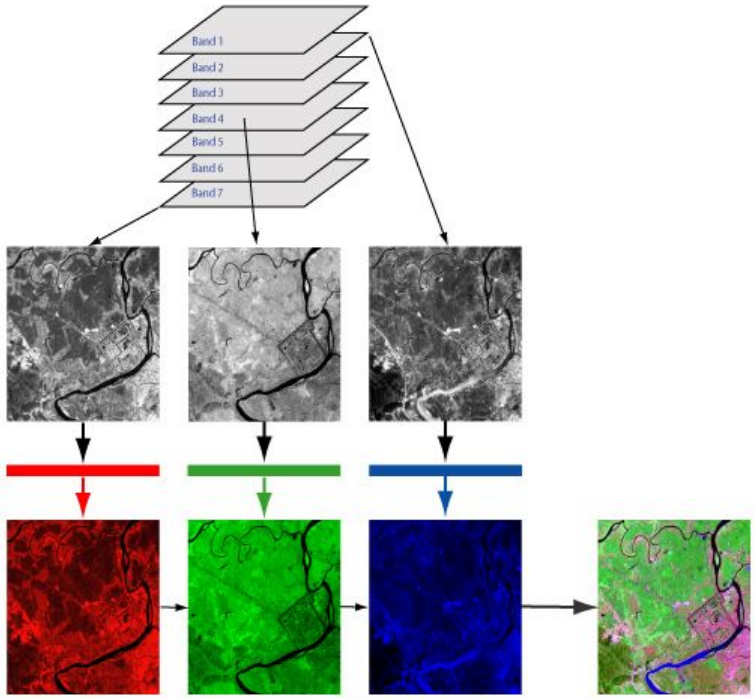


Figure 5.5: Image data combined from three sensor channels to produce a multi-spectral image. Such color-composite images aid visualization and interpretation of the land-cover. Brightness levels, shown as grey tones, represent values in the individual channels. A



In addition to the visible and near and shortwave-infrared regions, passive remote sensing systems also acquire data in the thermal region. Thermal energy is emitted by the land surface itself and, while rarely used for distinguishing types of land-cover, it facilitates the detection of clouds, active fires, and urban heat islands, as well as modeling various ecosystem processes and vegetation-climate interactions.

Active remote sensing

In active remote sensing, an instrument sends out a signal at certain wavelengths and measures the return time and strength of the back-scattered signal. RADAR and Light Detection and Ranging (LiDAR) are the most commonly used active remote sensing techniques for terrestrial applications.

In forest environments, RADAR information is primarily related to structural features at the scale of the wavelengths of the energy being sensed, versus optical sensors which measure reflected energy that is largely a function of canopy architecture, leaf pigments, and soil background. RADAR data provide information related to the density of leaves in the canopy, or branches and tree trunks, depending on the wavelength used.

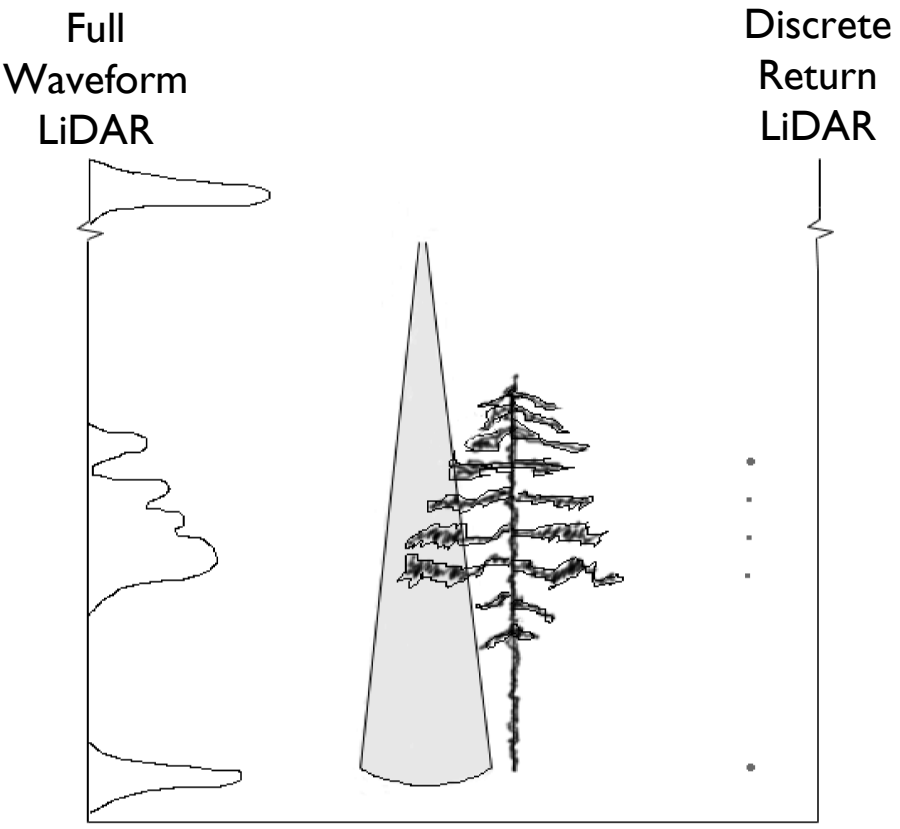
RADAR data are also sensitive to canopy and soil moisture, and are extremely influenced by topography. One major advantage of RADAR systems is their ability to penetrate clouds due to the longer wavelengths, the microwave portion of the EM spectrum. Because of their sensitivity to geometric properties of the forests, RADAR data have interesting potential for relating to forest biomass. RADAR data, and data from other satellite sources, were used to produce two recent maps of global forest biomass (Saatchi et al, 2011; Baccini et al, 2012).

Until recently, all RADAR sensors on board satellites collected measurements in only one wavelength band and one polarization. The resulting images did not have the dimensionality that multi-spectral images have, and thus yielded limited potential for classification of land-cover types. Recent satellites do have RADAR sensors that collect data in multiple bands and in different polarizations, thus extending their utility for classification of land-cover types. RADAR is further discussed in Section 5.5.

As with RADAR, LiDAR instruments emit a pulse of energy, some of which is scattered back to the sensor by the target. The distance between the sensor and the target is then calculated from the elapsed time for the LiDAR signal to make a complete round trip. However, in contrast to RADAR, LiDAR operates in the visible and near infra-red portions of the electromagnetic spectrum and, thus, does not penetrate clouds. Applications of LiDAR in forestry have mainly focused on measurement of canopy height, sub-canopy topography, and the horizontal and vertical distribution of vegetation; these parameters can be used to model estimates of aboveground biomass.

LiDAR systems are also generally classified into full-waveform LiDAR and discrete LiDAR systems, see Figure 5.6 below. Full-waveform systems record the entire waveform of a returning pulse, while discrete systems sample a discrete number of points, usually between one and five, per transmitted pulse. Both forms of LiDAR have been shown to be useful for estimating forest biomass via comparison with field data and modeling. While some LiDAR instruments collect data only along sampling lines, others have scanning abilities to collect data both along and across sampling lines, enabling the creation of images.

Figure 5.6: Example of full waveform vs. discrete waveform LiDAR (Lim et al., 2003)



The majority of LiDAR remote sensing to-date has been airborne-based. However, one LiDAR instrument, the Geoscience Laser Altimeter System (GLAS) on board the Ice, Cloud, and land Elevation Satellite (ICESAT) was satellite-based. Though the ICESAT satellite is no longer operational, GLAS provided full-form LiDAR information for linear tracks along the satellite path, with a ground resolution of 70m. The linear samples from GLAS were inputs to the two global biomass studies noted above.

Resolution and other considerations

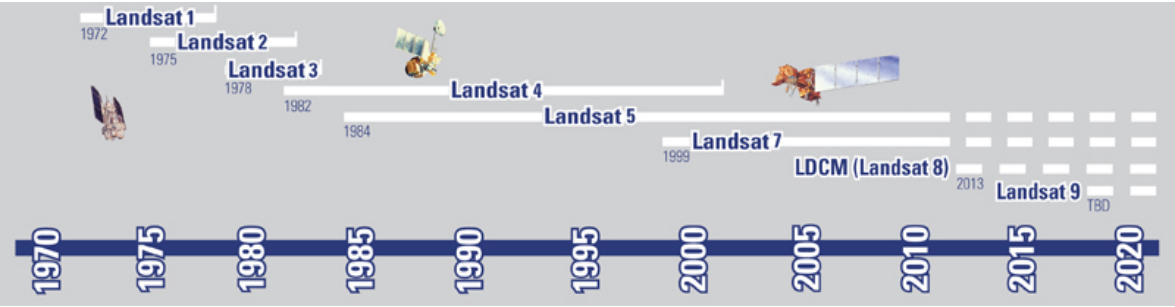
In addition to the type and spectral characteristics of different images, consideration must be given to: spatial and temporal resolution, the data collection strategy, and image archive length. Spatial resolution is important as the resolution must be fine enough to detect the changes of interest, i.e. at least half the size of the scale of changes. Publically available data have spatial resolutions ranging from 0.7m to 1km. Data used for land-cover monitoring have resolutions ranging from 10m to 30m. For example, A 30-m resolution observation, or pixel, represents a ground area of 900 m^2 (30*30m); a ground area of one hectare would be represented by 11 pixels at this resolution.

Data with coarser spatial resolutions are used for global studies and are not generally suitable for land-cover monitoring, as such data will not detect smaller-scale changes. The use of such data for land-cover monitoring yields an inherent bias in such derived estimates. On the other hand, very fine-scale data, less than 10m, has traditionally only been used over small areas because of cost. However, as such fine-scale data continue to become readily available and affordable, the use of these data over large areas, especially via sampling, is becoming more practical.

Temporal resolution refers to the frequency with which data are collected. Many satellites, such as Landsat, have defined orbits that dictate how frequently the satellite will return to view the same location on the earth and acquire a new image. The re-visit time for Landsat is 16 days and; the most that an area could be monitored is every 16 days. However, persistent cloud cover often reduces the frequency with which useable images are acquired. Other satellites, including many of the fine/small-scale sensors such as RapidEye, Quickbird, IKONOS, WorldView-2, SPOT HRV series, CBERS HRC, GeoEye-1 & -2, the DMC constellation, KOMPSTAT-2 or RESOURCESAT-1 are pointable, meaning they can be tilted to view a location that is at an angle to their defined orbit. While this can result in the same area being repeatedly imaged at much higher frequency, such acquisitions occur for short periods and require tasking, thus limiting the practicality of using such satellites in a monitoring capacity.

Data archive length is another important consideration for developing historical analyses, even for periods as brief as the past decade. To facilitate consistent monitoring and ease of logistics, it is preferable to work with a single source of data throughout a study period when possible. The Landsat series is the most common data source for monitoring land-cover change, as data extend back to 1972 for the multi-spectral scanner (MSS) and 1982 for Thematic Mapper (TM). Figure 5.7 illustrates the archive history of the Landsat satellite series. Further, as the Landsat satellites have a defined orbit, roughly the same area is acquired each time the satellite returns to view the same location on the earth, meaning image pairs from multiple dates mostly overlap.

Figure 5.7: Landsat archive timeline. Landsat 1 – 3 carried only the MSS instrument; Landsat 4 – 5 carried both the MSS & TM instruments; Landsat 7 carries the ETM+ instrument but since 2003 has experienced data gaps due to mechanical failure; the recently launched Landsat Data Continuity Mission (LDCM) (Landsat 8) carries the OLI and TIRS instruments. From http://landsat.usgs.gov/about_ldcm.php



Finally, a satellite program's future satellite launch and data acquisition strategy, as well as cost policies, are important considerations when planning a monitoring program. The Landsat Data Continuity Mission (LDCM), for example, ensures that future NASA satellites will continue to provide a long-term data record, including the successful launch of Landsat 8 in February 2013. Landsat's no-cost data policy allows flexibility in data use, and costs of other data sources are trending downwards. Current and future satellite data options and characteristics are provided in Appendix 5A, Table 5.3.

In summary, key data characteristics to consider are:

- What geographical, phenological, and atmospheric (especially persistent cloud cover) conditions exist?
- What are the spectral regions, and bands within them, where data are collected, and how do these relate to the potential for distinguishing the land-cover types of interest, and changes among them?
- What is the spatial resolution of the data and how appropriate is it relative to the scale of the land-cover changes to monitor?
- What is the temporal resolution in terms of potential frequency of acquisition of non-cloudy observations compared to the desired frequency of monitoring?
- What is the longevity of the image archive length – does this meet the historical mapping needs?
- What are the cost implications of these data in terms of purchase and analysis?
- What are the future satellite development and launch commitments?

5.4.2 Image pre-processing, analysis, and post-processing

Image pre-processing refers to any step that is applied to an image in preparation for the image analysis step, and image analysis is the process of generating a land-cover class for all parts of an image. Post-processing occurs after the image analysis step, and enables the estimation of rates and patterns of land-cover change to be generated.

Pre-processing usually includes geometric registration and co-registration, atmospheric correction, and occasional data transformation. Atmospheric correction may be necessary depending on the image analysis approach that will be used. Data transformation, though useful, is optional depending on the image analysis approach. As previously outlined, post-processing activities may include a number of steps. Finally, the calculation of change rates and error estimates are required. The summary of pre-processing, analysis, and post-processing steps below is based on optical data and approaches to classification, using examples of Landsat data analysis.

Image pre-processing

Geometric registration and co-registration

Geometric registration is the process of mapping data in a geographical coordinate system. This is to understand the geographical area represented and is an uncomplicated step applied when importing the image into a GIS or image-analysis format for processing.

However, geometric registration may have errors up to 100s of meters. Therefore, although images have been geometrically registered, it does not mean that images of the same area acquired from different dates will overlay well enough to avoid errors in change estimates resulting from poor co-registration. Therefore, co-registration may still be necessary. Co-registration is a standard, simple process that takes a modest amount of time and involves the identification of one image to use as the base image to which the remaining images will

be co-registered. Automation is increasingly available for processing numerous images, but traditional analyst-driven methods are also sufficient. The United States Geological Survey (USGS) has been reprocessing much of the Landsat archive, resulting in the creation of a L1T *precision and terrain corrected* product. These data have already been geometrically corrected using precision ground control points and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) information, yielding a dataset with accuracies within 30m and, thus, eliminating the need for further geometric correction. Co-registration among images should be reviewed and may require adjustments.

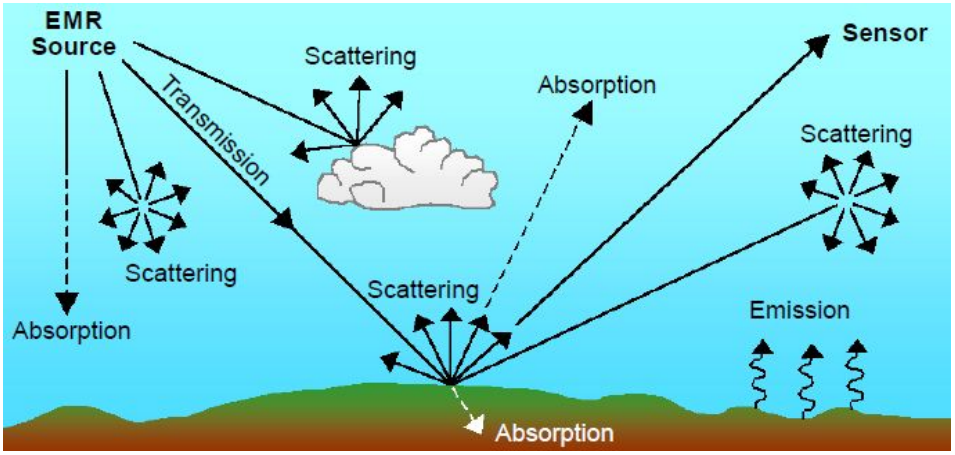
Atmospheric correction

The atmosphere has several effects on visible and infrared energy as it passes through the atmosphere from the sun to the land and back to a satellite or airborne sensor (Figure 5.8). Atmospheric correction is frequently performed in combination with a bi-directional reflectance distribution function (BRDF) correction. BRDF defines how light is reflected from a surface, and is dependent on both the incident and reflected directions.

Atmospherically-corrected images contain data recording surface reflectance, in unitless values from zero to one, as opposed to the digital numbers of the raw image data. Most atmospheric correction algorithms are applied to satellite images prior to mapping, and use a single correction algorithm for the entire image. These usually assume constant atmospheric conditions across an image, although there is active research on accounting for variability within an image.

Performing atmospheric correction depends on the image analysis approach used (Song et al., 2001). Approaches to classification that involve the creation of sub-classes for each type of land use and change can yield accurate maps without atmospheric correction because sub-classes can account for different atmospheric conditions. Conversely, methods that apply constant class signatures over images with variable atmospheric conditions should include atmospheric correction. Some semi-automated methods apply constant signatures over multiple images or image dates, and these methods are highly dependent on careful atmospheric correction.

Figure 5.8: Atmospheric effects on optical data. The electromagnetic radiation source is the sun, and this radiation can be blocked or scattered by clouds in addition to being affected by a "clear" atmosphere. A "clear" atmosphere still causes scattering and absorption of the radiation as it is transmitted from the sun to the earth and back to the satellite. Sun and sensor view angles also impact the effects of the atmosphere. BRDF characterizes how an object illuminated by a source, such as the sun, appears brighter or darker depending on the angle of the source and the angle at which it is viewed by a satellite sensor.



Several programs exist to perform atmospheric corrections over entire images. LOTRAN and 6S are the most common, and several tools have been created to facilitate their application. One example, developed by NASA, is the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) tool (Masek et al, 2008). LEDAPS uses information on water vapor, atmospheric pressure, ozone, a topography-dependent Rayleigh scattering correction, and an aerosol optical thickness component based on Kaufman et al (1997), to generate a surface reflectance value for each pixel. LEDAPS also generates water, cloud, cloud shadow, and snow masks.

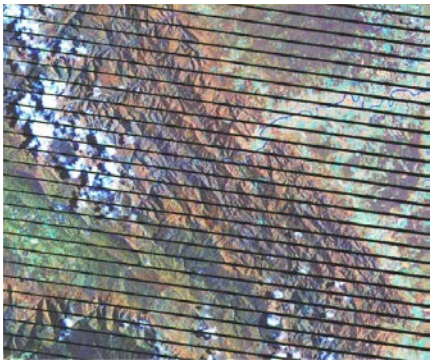
These corrections can be applied to several partially-cloudy images of the same area. The images can then be combined to produce a single, "gap-filled" composite mosaic. While the corrections are applied to all the images and the resulting composite should therefore appear seamless, atmospheric artifacts may remain, appearing as darker or brighter patches (Figure 5.9), and requiring each atmospherically-corrected image to be classified separately and then combined. Alternatively, additional algorithms based on, for example, local histogram matching could be applied to further reduce artifacts. In addition, beginning in summer 2013, all Landsat data, including those from the LDCM, will be available with top-of-atmosphere reflectance corrections applied.

Figure 5.9: Example of atmospheric correction of Landsat data from San Martin, Peru. A) shows an unstretched "true-color composite" where the red, green and blue bands are assigned to the red, green and blue colors in the display. The black lines are SLC-off data gaps. B) shows the same image, but a Gaussian stretch was applied to the data histogram. C) shows the near-infrared, middle-infrared and red bands assigned to the red, green and blue colors, a common assignment for a "false-color composite" that allows visual exploration of the infrared data. D) shows the same, but after atmospheric correction and a cloud / cloud-shadow mask have been applied using LEDAPS. Note that while the linear gaps have been filled, some of the cloud gaps remain since they were also cloud in the second image. Additional images are required to produce a cloud-free mosaic. E) shows a mosaic of two atmospherically corrected images, but with no histogram matching between them applied; note the orange-tone artifacts that appear to the left of the remaining cloud gaps in the upper-left of the image. F) shows the same two images combined into a mosaic image, but with histogram matching applied; note that the artifacts in E) are no longer visible.

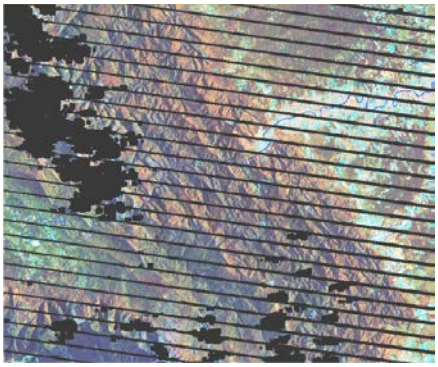
A)

B)

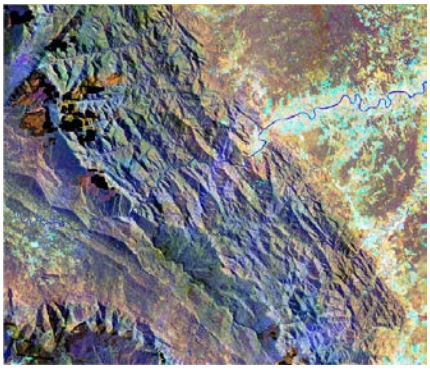
C)



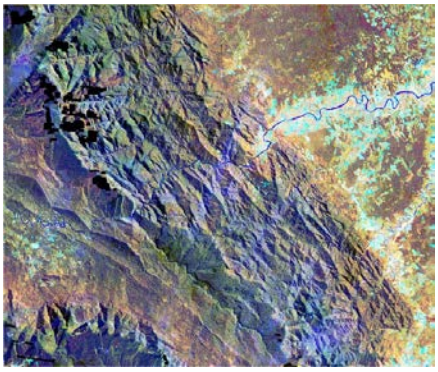
D)



E)



F)



Data transformation

Some analysis methods include data transformation techniques, such as various forms of ordination, prior to classification. Principal components analysis (PCA) is one example of a transformation technique involving ordination. These techniques alter the information to facilitate interpretation. The "Tassled Cap" transformation, for example, is a transformation with a long history of use in classification of vegetation types and based on PCA. Spectral mixture analysis (SMA) is another approach to data transformation. SMA utilizes estimated spectral reflectances of a set of "pure" features that are believed to make up the observed surfaces. In vegetated lands, for example, these are sunlit leaf, soil, and woody vegetation or litter. Soil theoretically could be split into multiple soil types with different reflectance properties, and water could also be included. Shadow is also generally included, as this is an important feature of most spectral images because of the geometry of the vegetated canopies.

SMA involves defining the spectral reflectance of each main feature believed to comprise most of the landscape under study and, based on these, estimating the proportions of each component for each pixel. The definition of the pure features can be via laboratory analysis, field analysis, or literature. When applied in SMA, they are referred to as "spectral end members," since they are located at the outer ends of the multi-dimensional distribution of the spectral data. End members can also be defined by simply selecting the extreme pixels in the multi-dimensional data; these are termed "image end members." However, if image end members are used, the resulting SMA analyses are relevant only to that image. An output could estimate, for example, that a particular pixel represents an observation of a piece of land that is 30 percent sunlit leaf, 20 percent soil and 50 percent shadow. These can be visualized as "fractional images" and used as inputs to classifications. SMA can be a useful approach in understanding the spectral data contained in the image data, as it explains the data in terms of physical features. Like PCA, and other types of data ordination, SMA does not add to the information content. Depending on the classification approach used, these techniques may help to produce more accurate or efficient classifications of land use.

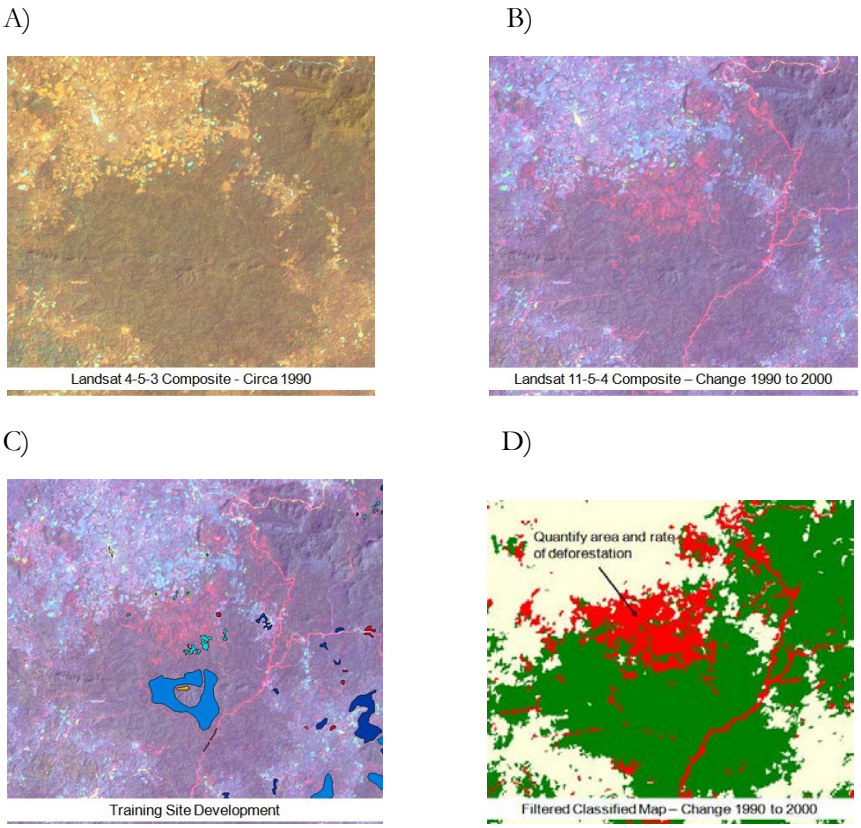
Classification

Land-cover classification produces a thematic representation of land by categorizing pixels based on their spectral signatures, and two broad types of classification exist; supervised and unsupervised.

In supervised classification, the analyst identifies "training sites" by delineating areas known to be of each class. Statistics of the pixel data within these areas are calculated and, at a minimum, these include the means, variances and co-variance matrix of the spectral data, defining the "spectral signature" of each class. The level of statistical separability among the classes can be evaluated, and this may suggest a need to merge or add additional sub-classes. Based on these statistics, various algorithms can be used to estimate the most likely class of the remaining, unidentified pixels, yielding a classified image.

Often, output classifications are evaluated and, based on conspicuous errors, training data are modified and a new iteration of the classification is run. Some of the common algorithms in remote sensing software packages are, in increasing complexity: Parallelepiped, Minimum Distance, Maximum Likelihood, and Mahalanobis Distance. Figure 5.9 illustrates the supervised classification approach.

Figure 5.10: Example of a supervised classification of two dates of images in a single process, from Liberia. Spectral images A) from two dates can be combined and viewed to more easily observe spectral changes B) indicative of land-use change. Training sites can be drawn C) based on field and aerial data as well as an analyst's knowledge of an area and expertise in interpretation. These are the basis for class statistics used to classify the rest of the image. The final product D) is often filtered to eliminate small and spurious errors.



In unsupervised classification, no training process is applied. Instead, algorithms identify spectrally similar pixels and then assign them to a user-specified number of groups. The output of an unsupervised classification is then reviewed by an analyst, and each group is labeled to a class based on the analyst's visual interpretation of the spectral data, the location of the pixels, and whatever ancillary field or other data are at hand. Additional iterations are typically run to further split groups that overlap different land-cover types. The ISODATA algorithm is common in most software packages.

An assumed advantage of supervised classification is that the analyst is directing the process more than in unsupervised classification based on *a priori* knowledge of the area being classified. Conversely, an assumed advantage of the unsupervised approach is that the algorithm evaluates the distribution of the data itself. In recent years, supervised algorithms that explore the distribution of the data while still allowing the analyst to direct the process via training, have become common. Two such algorithms are Decision Trees (DTs) and Neural Networks (NNs). DTs operate by iteratively seeking a binary split to the data in each of the bands, based on the data in the training sites identified by the analyst. The split is one that optimizes accuracy at that stage in the development of the DT. The final tree is often composed of hundreds of splits and terminal nodes representing the land-cover classes contained in the training data. "Boosting" and "pruning" can be applied to DTs in order to improve their efficiency and reduce the number of final splits. The resulting DT is a set of rules that is applied to the rest of the pixels to produce a classified image. Numerous studies have used DTs to generate robust classification results in many regions (Friedl et al, 1999; Hansen et al, 2000; Pal and Mather, 2003; Rogan et al, 2003; Hansen et al, 2008b).

NNs attempt to mimic the human learning process to associate a class with the image data. Many variants of NNs exist, and tend to run more slowly than DTs. Both DTs and NNs are becoming favored over maximum likelihood and other classification algorithms in recent years. Most recently, Random Forest ensemble classification methods have been successfully applied to land-cover and land-cover change classification (Pal, 2005; Gislason et al, 2006; Rodriguez-Galiano et al, 2012). This approach, unlike DTs, randomly selects some, but not all, of the variables to build the resulting tree and identifies resulting splits based only on this subset of variables. Such methods do not suffer from overfitting, which can be a problem with DTs, and generally perform efficiently.

All of the above approaches are examples of "per-pixel" classification, meaning the pixel is classified solely based on its spectral characteristics. Any of these methods can be expanded to become part of a contextual classification. In contextual classification approaches, a pixel is classified based on its own spectral characteristics as well as those of surrounding pixels. One type of contextual classification is textural classification. In this, the variance of the pixels within a certain window around the center pixel, e.g., a five-by-five pixel window, is used to inform the classification. Another type could use the average, or some other metric, of the pixels within the window. Weighting can also be used to apply different weights to pixels that are closer to, or farther from, the central pixel being classified.

Image segmentation, another contextual approach, is a statistical method that groups contiguous pixels into areas (segments) that are relatively homogeneous. Segmentation generally represents an intermediate step prior to classification, and segmentation algorithms allow an analyst to specify the relative size and shape of the segments. The resulting segmented image can then be classified at the segment level, rather than the pixel level, providing additional information that can be utilized by the classification algorithm, or by the analyst while developing the training data sites.

Each of the above approaches can be applied to a single image at a time, or to mosaics of images of the same area and time period. They can also be applied to multi-temporal image data, i.e., images from the beginning and end of a study period. This enables a direct estimation of change and persistence from the multi-temporal imagery. Some form of "direct change estimation" process is usually recommended for change estimation. This process also includes a single classification step that yields a two-date classification, rather than the classification of two individual images and two single-date classification outputs, both of which may contain errors. These errors would be compounded when the two maps are combined during post-processing.

Some more recent semi-automated approaches use much more of the data archive than a single image from a start date and another one from an end date. Some are based on the seasonal signal of different types of vegetation and estimate changes based on where anomalies in these seasonal signals are detected (see, for example, Friedl et al, 2010; Jiang et al, 2012). Others mine all available data and generate many multi-temporal metrics, such as "linear trend in red reflectance" or "maximum middle-infrared reflectance recorded since the initial date" (e.g., Hansen et al 2008a, 2008b). These are powerful because short-lived signals of land-use change are more likely to be captured, and all available data are employed, which may be critical in cloudy areas.

Replicability and analyst interaction versus automation

In the case of estimating deforestation, many studies with analyst interaction have produced accurate estimates of national forest cover. Accuracies have often been reported over 90 percent (e.g., Harper et al, 2007; Lindquist et al, 2008; Evans et al, 2010; Longépé et al, 2011); accuracies for land-use classes such as agriculture and grassland tend to be lower, generally 70 to 80 percent, and these estimates are generally derived from local rather than national studies.

In recent years there has been valuable research on developing automated methods for processing satellite data. This has mostly been in the pre-processing steps, although in some cases it has also included the classification step. For example, there are well-published approaches that use automation for a series of pre-processing steps, then the actual change estimation is conducted using a set of rules or digital classification

assisted by analyst interpretation (Souza et al, 2005; Masek et al, 2008). On the other hand, the recently published Deforestation Atlas of the Democratic Republic of the Congo was produced by an entirely automated approach (Hansen et al, 2008a).

There are a wide range of options to apply automation in the classification step itself. For example, classification algorithms could be rule-based. This would be in the form of thresholds applied to the reflectance data, or derived data in some other units. In this case the validity of the results would be very dependent on precise correction and normalization of the images in the pre-processing step. Further, if relatively few rules are used, the assumption that accurate results can be achieved over large areas using few rules must be valid. This is often not the case and should therefore be tested. It may be that such rules can be applied only to parts of the study area where the cover types are most easily distinguished with the spectral data, or to the classes that are most spectrally distinct, such as dark or clear water, snow, and bright non-forest areas such as urban areas and exposed sand and soil. This could lead to rapid estimation of cover and change for much of the country, while the remaining areas or classes can be estimated via other approaches.

Another example of automating the classification step could be to automate the process of collecting data on training sites. Hansen et al (2008b), for example, sampled an existing vegetation map to generate training points. While the results are encouraging, further testing should be conducted in other regions, especially ones with mountains and more deciduous vegetation. A related approach is to use traditional interpretation methods to identify training sites for classes, as is typically done in a supervised classification approach. A large set of training sites could be built for the entire country, or for various strata within it. Once it is confirmed that this set can be used to produce an accurate map, the same training sites could be applied to new data in later years to calculate new class spectral signatures to be used with the new imagery. The approach could be automated once a national training data set is defined, as the spectral variations in the new data are accounted for each time these new data are combined with the training site locations.

Countries may potentially automate all but the final steps of a methodology to estimate change. Another approach could be to automate the estimation of the most conspicuous changes, e.g., clear-cutting of forest, while applying a less-automated method to estimate the less conspicuous ones. Alternatively, a country could choose to monitor certain parts of the country that are more appropriate for automated monitoring, like areas with modest topography and cloud cover. Other more difficult areas may require more direct analyst interaction to obtain accurate results. The fact that the scientific community itself uses a broad range of approaches indicates that there is no single best answer and that countries should evaluate options themselves. In doing so, countries should seek an optimal balance between the accuracy of the final estimates, the replicability of the methodology and the cost.

Post-processing

Post-processing refers to any step conducted after the classification step, and the post-processing steps required will vary depending on the classification approach and attributes desired in the final map product used to calculate areas for categories.

If the classification methodology included the creation of sub-classes merged into the final desired classes, this should be done first. Each class in the digital output file of the classification has an assigned number, and merging can be accomplished by recoding the values of all the sub-classes to a value that represents the final class. If a two-date classification was not conducted, the following step should be applied to the two classifications to create a two-date change map. The values of the classifications from both dates should be recoded to form the basis for a final class map that records categories of change and persistence. However, note that the previous section recommends directly estimating change from multi-temporal images. With direct change detection, yielding a two-date classification, the output classifications will already have values representing classes of change and persistence and, therefore, the previous recoding step would not be required. Further, errors present in each of the single-date classifications would be compounded in the merged classification output.

After recoding to the final class values, some filtering of the product is usually desirable. Filtering is generally performed for two reasons. First, it eliminates many small errors associated with micro-topography and other very local effects that produce a speckled pattern of mis-classified raster cells. Note that we use the term cell instead of pixel when referring to classification outputs rather than spectral images. Some classification methods are more prone to producing these errors than others, but they are common artifacts that should be removed. A second reason for filtering is to eliminate patches smaller than a desired MMU or the minimum patch size in a national class definition.

Two broad types of filters are commonly used, and they can be used in sequence. The first are "local filters," and are based on the class values around (within a three-by-three window) a center cell. A common filter is a local majority filter, where the center cell is re-assigned to the most common cell value within the window. This not only removes the speckled pattern but also smoothes jagged edges, which may or may not be desired. For small windows, such as a three-by-three window, this is subtle. The second type of filter is a "sieve filter." In this, patches of cells with the same value are identified, and patches smaller than a user-defined size eliminated. As mentioned above, this is useful because the final product can have a defined MMU that meets a country's national definition of forest.

Calculation of change rates

Several factors must be carefully addressed in the calculation of change rates. First, the source images may not be from the exact beginning and end of the time period being reported, especially where cloud cover limits the coverage of optical images. For example, many studies that report changes over five or ten years use images that are within one or two years of each target date. In this case, the study areas should be divided into areas where the image pairs representing the start and end time have different lengths of time separating them. For example, for a 2000 – 2010 study, one part of the analysis may be based on images from 2001 and 2009, while another is from 1999 and 2011. These areas should be defined and recorded as having an eight and twelve-year difference in dates, and rates of change calculated for each area with a given difference, and for each forest stratum. In this case, each forest stratum experiencing change between the eight year difference would have an entry, and each forest stratum experiencing change between the twelve year difference would have an entry. This then allows a temporal extrapolation for each area in each stratum, in this case to a ten year period.

Another factor that must be addressed are data gaps from cloud cover or other reasons. If reporting in units of percent, one should consider if the sampled area, which may be the great majority of the study area, is representative of the entire study area. If reporting in absolute units, extrapolation is needed. This may warrant another stratification so that percent rates are not extrapolated into very different areas and thus not well-represented by those where data exist. After extrapolating the percent rates, rates can be converted to absolute values by combining with the forest area at the beginning of the reporting period. In this step, data on change can be combined with those on the forest strata, in order to report change for each forest stratum.

Third, if the analysis was not for a single-year period, the total rate should be reported for the entire time period of analysis, not in per-year units. In the above example of 2000 – 2010, if the aim is to report in units of percent per year, then a correction must be applied. This is calculated based on areas at the start and end date:

Annual change rate = [(area t2 / area t1) ^ (1 / (date t2 – date t1))] – 1

where t1 and t2 are the beginning and end of the time period of the study, in years (Puyravaud, 2003).

Error assessments

The estimation of error in a change product represents a very important component of the analysis as it provides explanation of, and validity to, the results. The main elements of an accuracy assessment are the error matrix, or confusion matrix, and associated statistics (Congalton, 1991). The error matrix is generated by

comparing the classification results with reference data that may come from various sources, i.e., field and aerial surveys. The statistics include overall accuracy, and the producer's and user's accuracy for each class in the product. The Kappa coefficient can also be calculated, but many articles highlight the limitations of this statistic (Olofsson et al, 2012; Pontius and Millones, 2011; Foody, 2002). In the example error matrix in Table 5.3, the columns contain verified land uses and the rows contain estimated uses from the classification. The values along the diagonal are the number of correctly classified pixels, and those off the diagonals are errors of omission and commission. Overall accuracy is the portion of the total number of correctly mapped pixels.

The producer's accuracy indicates how often a pixel is correctly assigned to a specific class. This statistic is based on errors of omission, i.e., how often a pixel was incorrectly omitted from the class. The user's accuracy indicates how often a pixel was incorrectly assigned to a given class. This is based on errors of commission, i.e., how often a pixel was incorrectly included in a class. In the example table, the producer's accuracy for degraded forest is: 100 x 1,890 / 2,040 = 92.6 percent. The user's accuracy for the same class is: 100 x 1.890 / 2,000 = 94.5 percent.

Table 5.3: Example of an error matrix. In this hypothetical case, the land use totals are the same as in the beginning time in Table 5.1

		Reference			
		Forest	Degraded Forest	Non-forest	Map total
Land-use map	Forest	9,880	90	30	10,000
	Degraded Forest	70	1,890	40	2,000
	Non-forest	10	60	3,930	4,000
	Reference total	9,960	2,040	4,000	16,000

Overall accuracy

Producer's accuracy (%)		User's accuracy (%)	
Forest	99.2	Forest	98.8
Degraded Forest	92.6	Degraded Forest	94.5
Non-forest	98.3	Non-forest	98.3

Both the land-use change and error matrices are common formats for reporting land-use change and errors. While they differ from the reporting-table format of the IPCC, shown at the end of Chapter 3, the data can easily be transferred. It is useful to calculate these statistics for the different strata in a study area as this allows one to combine the errors with errors in carbon stock for each stratum. It also allows one to assess where

improvements are most needed, i.e., which parts of the GHG inventory are contributing the greatest errors in GHG estimates and should be reviewed as part of the KCA.

The examples in Table 5.3 demonstrate error estimation in land-use cover for a single date. However, countries must estimate errors in change in land use over time. Multi-date accuracy assessments use the information available from two dates. An appropriate approach is the use of careful, cross-checked, visual interpretation of a combination of very high resolution imagery, along with imagery used in the classification itself. Multiple interpreters can be used, and the consistency of their interpretation can indicate confidence of the validation data set itself. Field surveys can be valuable for the most difficult classes to interpret even with very-high resolution imagery, such as degraded or lightly-degraded forest.

Error-adjusted area estimates, such as those described in Olofsson et al (2013), use the information available in the matrix, together with the total area of each class identified in the map, to generate area-adjusted errors based on the proportional area of each class and errors identified in the matrix. Error matrices and accuracy assessments can also be extended to provide confidence interval (CI) information. This is especially important as it quantifies the confidence of a particular class, thus providing very pertinent additional information. Olofsson et al. (2013) describe a process for creating CI bounds based on area-adjusted error matrices

In addition, it is important to account for a rare class when developing a validation strategy (Stehman et al, 2010). This type of proportional sampling design ensures that adequate sampling occurs in sparser yet critical classes, such as deforestation. The sampling design could focus on areas of deforestation identified in the map, and a stratification could be used to categorize areas of high change probability and low change probability. Proportional sampling could then be focused in these strata to ensure each class is adequately represented in the validation analysis.

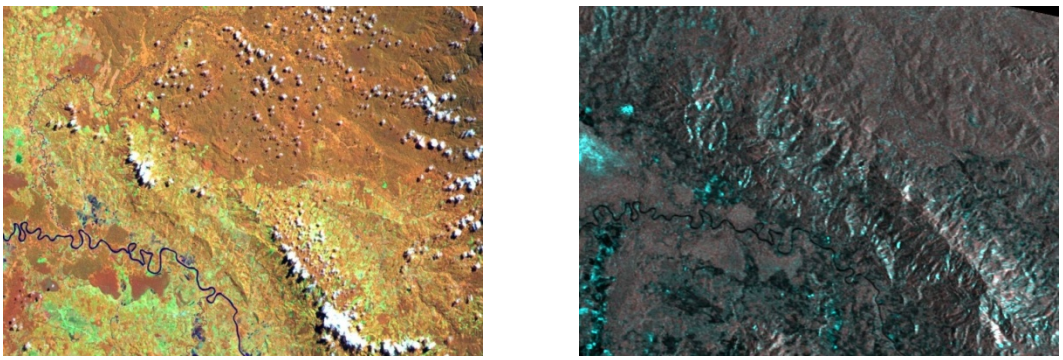
5.5 EMERGING AREAS OF RESEARCH

Two areas of particularly active research in support of REDD+ activities include the mapping and monitoring of degradation, and the use of other sources of remotely sensed data, such as RADAR. Forest degradation is a substantial contributor to GHG emissions from land-use change (Nepstad et al, 1999; Souza and Roberts, 2005; Stickler et al, 2009; GOFC-GOLD, 2012; Hirata et al, 2012), with estimates ranging from 20 to 50 percent of total land-use GHG emissions over large regions (see, for example, Houghton and Hacker, 1999; Lambin et al, 2003; Asner et al, 2005). Mapping and monitoring of forest degradation remains challenging. Multiple definitions of forest degradation exist, adding to the complexity of mapping and monitoring forest degradation. For example, the IPCC's definition of forest degradation is provided above in section 5.2.1. Conversely, GOFC-GOLD (2012) presents a range of human activities that result in forest degradation including selective logging, forest fires (canopy and sub-canopy) and fuelwood collection. GOFC-GOLD (2012) lists a range of human activities that result in forest degradation including selective logging, forest fires (canopy and sub-canopy) and fuelwood collection. These different activities may require different monitoring approaches, and a country should seek to understand the implications and applicability of different approaches.

A second area of research in support of REDD+ activities is the use of other sources of remotely sensed data, such as RADAR, to map and monitor forest extent and characteristics, deforestation, and degradation. Several characteristics make RADAR an attractive source of information for such applications. First, because RADAR sensors operate in longer wavelengths (generally 1cm to 1m) of the EM spectrum than, for example, optical sensors, they are able to penetrate clouds and are thus useful for monitoring in areas with persistent cloud cover. In addition, because the signals received by the sensor are less affected by atmospheric conditions, and the properties of the emitted radiation from active sensors are controlled and well known, RADAR images are directly comparable over time. RADAR signals are also sensitive to the geometric properties of a forest, providing information on the distribution of aboveground biomass. Figure 5.10 illustrates a detail of a Landsat image compared to a PALSAR satellite image for an area in San Martin, Peru.

Figure 5.11: Examples of Landsat and RADAR images, from Peru. Ground observations in the Landsat data in A) are partly obscured by clouds, while the PALSAR image in B) is cloud free. While the brightness variations in both are affected by terrain, this is more noticeable in the latter

A) B)

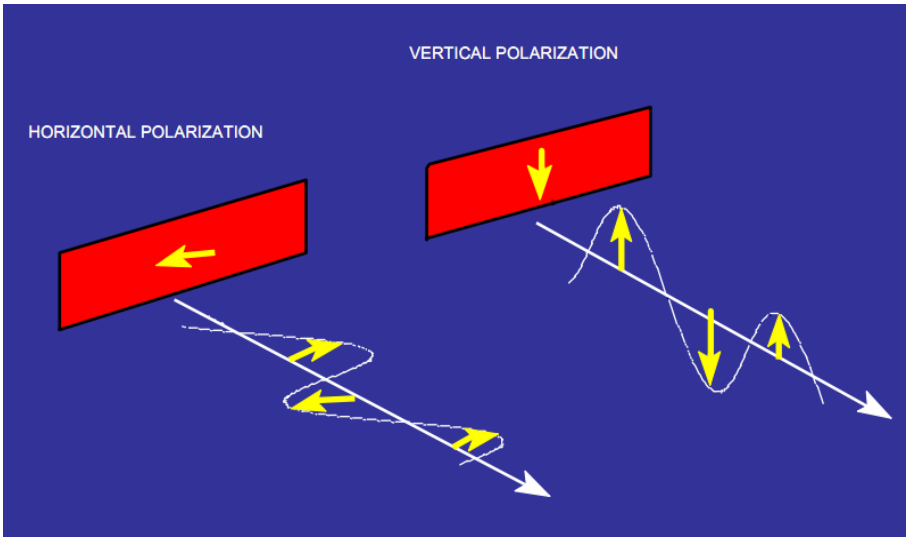


The following provides a brief introduction to a selection of active remote sensing concepts. Such concepts are key to understanding the basic characteristics of active remote sensing data. RADAR measures the distance between an object on the ground and the sensor based on the strength of radio waves that are transmitted as pulses of microwave beams, directed by an antenna, that illuminate a strip of the earth's surface (swath). The intensity of the signal that is scattered back to the receiver from this transmitted energy is recorded as the returned signal, and the distance is calculated based on the time elapsed for the RADAR signal to make a complete round trip. The next transmitted pulse illuminates the next strip of terrain along the swath, and a two-dimensional image is created (each pulse defines one line).

Several concepts unique to RADAR are also useful to understand, including phase, polarization, side-looking instruments, Synthetic Aperture RADAR (SAR), interferometry, and polarimetry. Phase describes the relationship of the lead, or lag, of an electromagnetic wave with respect to a reference wave of the same wavelength, and is expressed in degrees. 360 degrees represents one complete cycle and, therefore, a wave that is lagging one quarter of a wavelength behind the reference has a phase of 90 degrees. Polarization refers to the orientation of the electric field with respect to the direction of propagation. Unlike optical remote sensing, where electric fields of different waves have no definite orientation and the radiation is therefore unpolarized, in active remote sensing the electric field of the resulting radiation has a preferred orientation. Linear is the most common polarization used in RADAR remote sensing where a radiated electric field is oriented either horizontally (horizontal polarization) or vertically (vertical polarization) with respect to the direction of propagation, as shown in Figure 5.11. A sensor that can transmit either horizontally (H) or vertically (V) polarized waves and receive both will result in the following four polarized images:

- HH: horizontal transmission and horizontal reception;
- VV: vertical transmission and vertical reception;
- HV: horizontal transmission and vertical reception; and
- VH: vertical transmission and horizontal reception.

Figure 5.12: Horizontal and vertical polarization



While some space-borne satellites including RADARSAT-1 and ERS-1/2, have only single polarization (RADARSAT-1 with HH and ERS-1/2 with VV), other satellites, including RADARSAT-2, ENVISAT and ALOS/PALSAR acquire data with all four polarizations ("quad-pol") or two polarizations ("dual-pol").

Most RADAR sensors are also side-looking instruments, unlike many optical sensors which acquire imagery at nadir (i.e., observing a location directly below the sensor). This across-track capability, termed Side Looking RADAR (SLR), introduces a range of geometric distortions including foreshortening, layover, and shadows that require full, or partial, correction.

Some RADAR remote sensing systems, such as SAR systems, are able to achieve a relatively high resolution without the use of a large antenna. Data from such systems are generally processed by data distributors to Single Look Complex level data, containing both amplitude and phase information, and a range of derived products which are usually geocoded, ortho-rectified, and radiometrically corrected. And, while some geometric and radiometric distortions due to terrain relief may persist, these processed and derived products are generally more appropriate for use in mapping. Among the distortions that may persist is speckle. SAR speckle causes pixel-to-pixel variation in intensities even over a homogenous area; this grainy 'salt and pepper' texture degrades the quality of the image and complicates interpretation. Speckle can be reduced by averaging the backscatter response within a pixel, though this can effectively reduce resolution, or by applying smoothing filters.

As with optical sensors, RADAR sensors exploit different wavelength bands. A shorter wavelength band, such as an X-band (λ= 3 cm) may only penetrate the upper layer of a forest canopy, whereas a P-band (λ= 23 cm) may penetrate leaves and small branches thus providing information about both the big branches and stems of the trees. Thus, resulting P-band images are important for measuring vegetation biomass and aboveground carbon stocks.

The surface roughness, geometric shape and dielectric properties of an object also affect the information received by the RADAR sensor. Surface roughness is a relative term that is dependent on the RADAR wavelength. For example, small objects such as leaves and twigs are considered rough for small wavelength

RADAR, but smooth for longer wavelength RADAR such as P-band RADAR. Water bodies tend to be relatively smooth, with most of the energy being reflected away from the RADAR, while trees and other vegetation are rough, causing backscatter, and thus have a bright appearance in a RADAR image.

The difference in intensity of RADAR returns from two surfaces of equal roughness is an indication of the difference in their dielectric properties, and these are strongly affected by their moisture. For example, the brightness of areas covered by bare soil may vary depending on the roughness and moisture content of the soil. For soil types of similar roughness, the surface with a higher moisture content will appear brighter.

Another relevant RADAR concept is SAR interferometry. As mentioned in the introduction, a RADAR image contains information about the intensity of the signal and the phase. If two SAR images have been acquired over the same area from very close antenna positions, the different path lengths from these positions to the object on the earth's surface cause the differences in phase. The path difference is geometrically related to the distance between two antennas and the terrain height. Since the antenna positions are precisely known, the observed phase differences can be used to infer three-dimensional information about the terrain height. The technique is known as SAR Interferometry.

Finally, SAR polarimetry is a relevant RADAR concept. As previously discussed, more parameters can be measured from polarimetric RADAR compared to single-channel RADAR. The different polarization bands may contain unique and additional information about the surface object. For example, a signal that reflects off a tree trunk to the ground surface is likely to show distinctive polarization shifts from signals that return directly off the soil. Surface objects that scatter are vertically oriented and show high backscatter in vertically polarized imagery and low backscatter in horizontally polarized imagery. Such unique information in different polarization bands is important for discriminating different land-cover types.

5.5.1 Applications of SAR

Applications on the use of SAR data for forest mapping, and in measuring and monitoring aboveground biomass (AGB), as well as scaling-up ground-based AGB measurements are increasing. Multiple studies have tested the potential of combined RADAR channels of different frequencies and polarization for deforestation monitoring. For example, Saatchi et al (1997) used C-SIR data to map land-cover types and monitor deforestation in the tropics, with an emphasis on characterizing several clearing practices and forest regeneration characteristics. They also mapped forest patches and fragmentation and found these data helpful in delineating areas with different degrees of forest disturbance. Rignot et al. (1997) compared SIR-C data with Landsat TM in a test site in Rondonia, Brazil, and while the Landsat TM yielded a more accurate deforestation extent classification, the combined use of both Landsat and RADAR imagery further improved the mapping accuracy.

The recent systematic availability of fully polarimetric SAR data from the ALOS-PALSAR, ENVISAT, and RADARSAT-2 has led to further land-cover classification research using SAR imagery. Walker et al. (2010) assessed the ability of PALSAR and LANDSAT data to classify and map forest cover in the Xingu River headwaters in southeastern Amazonia, producing overall accuracies of 92 and 94 percent with PALSAR and Landsat respectively for the forest versus non-forest classifications. They also found a high degree of spatial similarity among maps derived from PALSAR, Landsat, and the *Projeto* De Estimativa De Desflorestamento da Amazonia (PRODES), the Brazilian Amazon deforestation monitoring program.

In addition to polarimetric information, polarimetric interferometric SAR (PolInSAR) provides interferometric information related to the structure and complexity of the observed objects. Substantial improvements in land-cover change classification can be achieved by combining polarimetric and polarimetric interferometric information (Shimoni et al, 2009). In addition, the fusion of spatial and textural information derived from various SAR polarizations has been shown to improve the classification results (Borghys et al, 2006).

As mentioned above, SAR data are also being evaluated for scaling up ground-based AGB and monitoring changes over large scales (Lu, 2006; Mitchard et al, 2009). These data are both sensitive to the geometric properties of the forest, and directly related to measurements of AGB. However, this sensitivity appears to saturate at biomass levels of around 100 tons ha^{-1} (Imhoff et al, 2000) and approximately 81 percent of global forests are above this saturation limit (Nelson et al, 2007).

Recently, data from PALSAR, the first long wavelength (L-band, 25 cm) SAR satellite with the capability to collect cross-polarized responses, has yielded improved estimates of AGB with little or no saturation up to 250-300 tons per hectare based on the sensor's cross-polarized ability to exploit the strong response of three dimensional objects, such as trees, compared to bare soil. Mitchard et al (2011) used L-band synthetic aperture RADAR backscatter data from 1996 and JERS-1 and PALSAR data from 2007 to produce biomass maps of a forest–savanna ecotone region in central Cameroon characterized by small scale deforestation and degradation, and found the RADAR data detected changes in a broad AGB class in forest–savanna transition areas with an accuracy of 95 percent. Similarly, Ryan et al (2012) generated biomass maps and changes in carbon stocks with known uncertainties using PALSAR imagery in a region in central Mozambique yielding maps with sufficient accuracy to enable changes in forest carbon stocks of as little as 12 tons per hectare over 3 years with 95-percent confidence to be detected. Mitchard et al (2012) used a combination of PALSAR, space-borne LiDAR (ICESAT GLAS), and ground-based data to map AGB in Gabon's Lopé National Park.

While these results highlight the potential for space-borne imaging RADAR in the design of robust forest monitoring systems and AGB estimates in tropical countries, several limitations exist and the history of SAR data usage for land-cover classification remains relatively recent.

For example, one major limitation of SAR data utilization and analysis is the difficulty involved in interpreting RADAR backscatter as compared to optical spectral data (Saatchi et al, 2000). The presence of topographic effect and speckle complicates both visual and digital analysis of RADAR images, and complex areas with a greater abundance of secondary forests may yield significantly lower accuracies. Additional evaluations are also needed to assess the utility of newer RADAR data sources in mountainous areas.

Uncertainty related to the long-term data continuity of space-borne RADAR systems could also prove a limiting factor for forest monitoring. For example, neither PALSAR nor ENVISAT, which both provided fully polarimetric L-band data, continue to collect data and even though the Japanese Space Agency has been testing PALSAR-2 and planning a launch in August 2013, there may be no L-band polarimetric satellite data for at least two years.

While the range of advanced SAR processing techniques capitalizing on the availability of multi-polarimetric information is evolving, and classification methods based on the polarimetric decomposition are being developed, SAR data generally yield less robust results than Landsat data for forest/non-forest classification in most studies.

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5.7 COMMONLY USED SATELLITE DATA SOURCES FOR LAND-USE MONITORING

Sensor	Satellite – Agency	Swath Width	Resolution	Repeat Cycle	Systematic Acquisitions	Operational Status	Monitoring Applications
Landsat 7 ETM+	Landsat 7 - NASA	165km	15m panchromatic 30m multispectral 60m thermal	16-21 days	Yes	Yes, with SLC-off gaps	deforestation, encroachment, roads, log ponds
ASTER	Terra - NASA	60km	15m multispectral	Varies	No	Partial (no SWIR channels)	deforestation, encroachment, roads, log ponds
SPOT-5	SPOT - Astrium	60km	20m multispectral 5m panchromatic (2.5m interpolated)	Varies	No	Yes	deforestation, encroachment, roads, log ponds
CCD	CBERS-2B – INPE	113km	20m multispectral	26 days	Yes	Yes	deforestation, encroachment,
HRC	CBERS-2B – INPE	27km	2.7m panchromatic	26 days	Yes	Yes	skid trails, illegal fishing vessels
MODIS	Terra / Aqua – NASA	2330km	250m visible 500m multispectral 1km thermal	4 times per day (diurnal / nocturnal)	Yes	Yes	fires, large-scale deforestation
AWIFS	Resource Sat-1	730km	56m	5 days	Yes	Yes	large-scale deforestation
IKONOS	IKONOS – GeoEye	Varies	4m multispectral 1m panchromatic	Varies	No	Yes	skid trails, canopy gaps, illegal fishing vessels / logging vehicles
GeoEye-1	GeoEye-1 - GeoEye	Varies	0.4m panchromatic (resampled to 0.5m) 1.65m multispectral	Varies	No	Yes	skid trails, canopy gaps, illegal fishing vessels / logging vehicles
QuickBird	QuickBird – Digital Globe	Varies	0.6m panchromatic 2.4m multispectral	Varies	No	Yes	skid trails, canopy gaps, illegal fishing vessels / logging vehicles
WorldView-2	WorldView-2 Digital Globe	Varies	0.5m panchromatic 1.8m multispectral	Varies	No	Yes	skid trails, canopy gaps, illegal fishing vessels / logging vehicles
Radarsat-2	CSA	varies	8 m quad pol fine	24 days	varies	Yes	deforestation, roads, log

			25 m quad pol standard 100 m wide				ponds
ASAR	ENVISAT-ESA	varies	30 m polarization mode 150 m Wide Swath mode 1 km Global Monitoring mode	36 days	varies	No	deforestation
PALSAR	PALSAR-JAXA	varies	9 m Single pol 19 m dual pol 30 m quad pol 100 m Scan SAR	45 days	Yes- all mode No- quad pol	No	deforestation, roads, log ponds

Future Missions

Sensor	Satellite – Agency	Swath Width	Resolution	Repeat Cycle	Systematic Acquisitions	Operational Status	Monitoring Applications
Landsat 8 OLI	LDCM - NASA	185km	15m panchromatic 30m multispectral 100m thermal	16-21 days	Yes	Launch date Dec. 2012	deforestation, encroachment, roads, log ponds
VIIRS	NPV – NASA	3000km	750m	2 times per day	Yes	recently launched, in calibration	fires
PALSAR-2	PALSAR-JAXA	varies	1-3 m Spotlight 3-10 m Stripmap 100 m Scan SAR	15 days	Varies	Aug-Oct 2013	deforestation, encroachment, roads, log ponds

5.8 SELECTED RESOURCES

Online guides and other materials

United Nations Space Science and Technology:

http://www.unoosa.org/oosa/en/SAP/centres/index.html

Systems for World Surveillance, Inc.:

http://www.rsat.com/tutorials.html

Biodiversity Informatics Facility:

http://biodiversityinformatics.amnh.org/index.php?section_id=17

European Space Agency Earthnet:

http://earth.eo.esa.int/download/eoedu/Earthnet-website-material/to-access-from-Earthnet/

NASA Earth Observatory

http://earthobservatory.nasa.gov/

Software

EXELIS: ENVI

http://www.exelisvis.com/ProductsServices/ENVI.aspx

INTERGRAPH: ERDAS Imagine

http://geospatial.intergraph.com/products/ERDASIMAGINE/ERDASIMAGINE/Details.aspx

PCI Geomatics

http://www.pcigeomatics.com/

American Museum of Natural History (AMNH) Biodiversity Informatics Facility, Open source GIS and remote sensing software

http://biodiversityinformatics.amnh.org/index.php?section_id=33&content_id=138

GRASS GIS

http://grass.fbk.eu

IDRISI GIS and Image Processing Software

http://www.clarklabs.org/products/idrisi.cfm

Random forests Software

http://www.stat.berkeley.edu/~breiman/RandomForests/cc_software.htm

Rulequest data mining tools; See5 classification software

http://www.rulequest.com/see5-info.html

R statistical language

http://www.r-project.org/

Open source

Alaska Satellite Facility - Map Ready, SAR Tool Kit

http://www.asf.alaska.edu/downloads/software_tools

ESA – polsarpro (Polarmetric SAR Data Processing and Educational Tool)

http://earth.eo.esa.int/polsarpro/

NEST – Next ESA SAR toolbox

http://nest.array.ca/web/nest/release-4B-1.1

RAT – Radar Tools

http://radartools.berlios.de/

Data access

USGS Earth Resources Observation and Science Center (EROS)

http://glovis.usgs.gov/

(Landsat Archive, Global Land Survey (GLS) data, as well as various ASTER and MODIS products)

USGS LandsatLook Viewer

http://landsatlook.usgs.gov/

(Enables searching of both LandsatLook images & Level1 Landsat data)

National Research Institute (INPE) of Brazil

http://www.dgi.inpe.br/CDSR/

(Range of Landsat and CBERS imagery, as well as various MODIS products)

Global Land Survey (GLS) 2005 products: Global Land-cover Facility

http://www.land-cover.org/data/

(Range of data sources including the Landsat archive and selected imagery for a range of instruments including ASTER, Ikonos, Quickbird, Orbview, and MODIS)

SPOT Catalog

http://catalog.spotimage.com/PageSearch.aspx?language=UK

(Access to the SPOT satellite archive)

Earth Remote Sensing Data Analysis Center (ERSDAC)

http://imsweb.aster.ersdac.or.jp/ims/cgi-bin/dprSearchMapByMenu.pl

(Access to the ASTER imagery archive)

Global biomass data

The following are two recently-published maps of global forest biomass, with a 1-km resolution, based on a suite of satellite data inputs, calibrated with plot data. These may be useful for national stratification of field sampling of biomass in a MRV system.

A. Baccini, S J. Goetz, W.S. Walker, N. T. Laporte, M. Sun, D. Sulla-Menashe, J. Hackler, P.S.A. Beck, R. Dubayah, M.A. Friedl, S. Samanta and R. A. Houghton. Estimated carbon dioxide emissions from tropical

deforestation improved by carbon-density maps. 2012 Nature Climate Change, http://dx.doi.org/10.1038/NCLIMATE1354

http://www.whrc.org/mapping/pantropical/carbon_dataset.html

Saatchi S, Harris NL, Brown S, Lefsky M, Mitchard ET, Salas W, Zutta BR, Buermann W, Lewis SL, Hagen S, Petrova S, White L, Silman M, Morel A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. Proc Natl Acad Sci U S A. 2011 Jun 14;108(24):9899-904. http://carbon.jpl.nasa.gov/

Tutorials

The remote sensing tutorial: Federation of American Scientists (FAS)

http://www.fas.org/irp/imint/docs/rst/Front/tofc.html

General remote sensing: Canada Centre of Remote Sensing

http://www.nrcan.gc.ca/earth-sciences/about/organization/organization-structure/canada-centre-for-remote-sensing/11740

USGS Change-tracking tool

http://pubs.usgs.gov/gip/133/

NASA fundamentals of remote sensing

http://gcmd.nasa.gov/records/remote_sensing_tutorial-00.html

Introduction to remote sensing - Virtual Hawaii

http://satftp.soest.hawaii.edu/space/hawaii/vfts/oahu/rem_sens_ex/rsex.spectral.1.html

NOAA's Satellite and Information Service: Learning About Satellites and Remote Sensing http://noaasis.noaa.gov/NOAASIS/ml/education.html

An introduction to remote sensing

CSIRO - http://www.cmis.csiro.au/rsm/intro/

An introduction to radar remote sensing: Canada Centre of Remote Sensing

http://www.nrcan.gc.ca/earth-sciences/geography-boundary/remote-sensing/radar-remote/2122

Radar polarimetry: Canada Centre of Remote Sensing

http://www.nrcan.gc.ca/earth-sciences/geography-boundary/remote-sensing/radar/1893

ESA's RADAR Tutorial

http://earth.esa.int/applications/data_util/SARDOCS/spaceborne/Radar_Courses/

ESA's Synthetic Aperture radar: Land applications tutorial http://earth.eo.esa.int/download/eoedu/Earthnet-website-material/to-access-from-Earthnet/2008_Bilko-SAR-Land-Applications-Tutorial/sar_land_apps_1_theory.pdf

6.0 REPORTING AND VERIFICATION: ELEMENTS AND GUIDANCE

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6.1 INTRODUCTION

According to the decisions adopted by governments working under the aegis of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), developing countries[11] that are willing to take action on REDD+ will have to establish a national forest monitoring system to assess anthropogenic forest-related greenhouse gas (GHG) emissions by sources and removals by sinks (UNFCCC, 2010). As actions to reduce emissions from deforestation and forest degradation (REDD+) should be results-based, developing countries will have to demonstrate that they are reducing emissions from deforestation compared to a reference level or baseline, also known as a Forest Reference Emission Level (REL) or Reference Level (RL).

In any international system in which an accounting procedure is foreseen, including the UNFCCC and its Kyoto Protocol, and probably any future REDD+ mechanism, the information reported in a country's GHG inventory represents the basis for assessing that country's performance, as compared to its commitments or RELs and could also form the basis for assigning any eventual incentives or penalties. Under the UNFCCC, information reported in GHG inventories provides the means by which the international community can monitor progress made by countries in meeting their commitments and in achieving the Convention's ultimate objective.

The quality of GHG inventories relies not only upon the robustness of the science underpinning the methodologies and the associated credibility of the estimates, but also on the way the information is compiled and presented. Information must be well-documented, transparent and consistent with specific reporting requirements and protocols (e.g., those under the UNFCCC) and guidelines included in voluntary or compliance schemes and processes.

The following elements are covered in this chapter:

- Key considerations for reporting – including an overview of requirements and mechanisms

[11] In this section, we will use the terms "developed countries" and "developing countries" as synonyms to the UNFCCC terms "Annex I Parties" and "non-Annex I Parties," respectively. However, in some cases, the UNFCCC terms may be used to accurately quote texts and requirements under the UNFCCC.

- An overview of reporting worksheets and tables contained in the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance on Land Use, Land-Use Change and Forestry (GPG-LULUCF)
- An overview of software options available to facilitate reporting
- Verification considerations and approaches included in the GPG-LULUCF

6.2 REPORTING

Reporting for REDD+ can be defined as the process used to translate information resulting from measurements or monitoring (for example, information generated by a forest carbon inventory and a land-use change analysis) into an agreed format, such as the UNFCCC reporting framework. It encompasses the amount of GHG emissions avoided as result of reduced deforestation and forest degradation, as well as the amount of GHG removals as a result of forest conservation and enhancement activities. Depending on the specific activity, other reported information may include data on forest areas affected, methodologies employed, emission factors used, impact on deforestation drivers, effectiveness of measures put in place, financial resources needed or used, or application of quality assurance/quality control (QA/QC) procedures. The reported information is often used to help improve the transparency of actions and to verify emissions and removals claimed for different activities.

6.2.1 Reporting requirements under the UNFCCC

Under the UNFCCC, all countries are required to provide national inventories of anthropogenic GHG emissions by sources and removals by sinks of all GHG not controlled by the Montreal Protocol (see Box 6.1). To promote the provision of credible and consistent GHG information, specific reporting guidelines have been developed detailing standardized requirements for reporting of GHG emissions and removals based on IPCC methodologies. These requirements differ across countries taking into account their specific capacities and capabilities. For example, reporting requirements for developed countries are more detailed and stringent in terms of the amount of information provided and the frequency of reporting.

Given the potential relevance of a future REDD+ mechanism, and the consequent need for robust and defensible estimates, the reporting requirements of developing countries on emissions from deforestation will certainly become more detailed (and possibly more stringent) following the GPG-LULUCF (IPCC, 2003). In fact, the agreement during REDD+ negotiations that the demonstration of REDD+ activities should produce estimates that are "results based, demonstrable, transparent, and verifiable, and estimated consistently over time"[12] reiterates this (UNFCCC, 2007). Although at present it is not possible to foresee the exact reporting requirements of a future REDD+ mechanism, they may follow the general principles and procedures currently valid for developed countries under the UNFCCC.[13]

Inventory data on GHG emissions and removals can be reported in the following ways:

- In national communications (NCs)
- In annual national GHG inventory reports (only for developed countries)

[12] Annex to Decision 2/CP.13. http://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf

[13] Methodological issues on REDD+ are under consideration within the UNFCCC process.

- In biennial update reports (BURs)
- In the context of nationally appropriate mitigation actions.

A summary of existing UNFCCC reporting requirements for developed and developing countries is given in Table 6.1.

Box 6.1: General provisions of the Convention relating to reporting of information

Article 4 (http://unfccc.int/essential_background/convention/background/items/1362txt.php), Paragraph 1 (a), of the Convention sets the obligation for all countries – taking into account their common but differentiated responsibilities and their specific national and regional development priorities, objectives and circumstances – to "develop, periodically update, publish and make available to the Conference of the Parties... national inventories of anthropogenic emissions by sources and removals by sinks of all GHGs not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the COP."

Article 12 (http://unfccc.int/essential_background/convention/background/items/1379.php) of the Convention requires each country to communicate to the COP the following elements of information:

(a) "A national inventory of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, to the extent its (a country's) capacities permit, using comparable methodologies to be promoted and agreed upon by the Conference of the Parties";

(b) "A general description of steps taken or envisaged by the Party (the country) to implement the Convention"; and

c. "Any other information that the Party (the country) considers relevant to the achievement of the objective of the Convention and suitable for inclusion in its (the country's) communication, including, if feasible, material relevant for calculations of global emission trends".

The Convention specifies the time frame for initial communications, but does not establish a frequency for submission, which is determined through decisions of the COP.

National communications

National communications from developing countries provide information on: the ongoing and planned actions to address climate change; GHG emissions and removals; adaptation and mitigation measures to climate change; sustainable development; financial and technological transfers; and capacity building activities. The preparation and delivery of NCs depends on the availability of resources, both human and financial, and on the institutional arrangements put in place for this purpose.

Guidelines for the preparation of NCs from developing countries were first adopted at COP 2 (Geneva, 1996) and subsequently revised at COP 8 (New Delhi, 2002)[14]. To facilitate the usage of these guidelines, the

[14] The latest version of the reporting guidelines are included in the Annex to Decision 17/CP.8. For the full text of these guidelines, see: http://unfccc.int/resource/docs/cop8/07a02.pdf#page=2.

UNFCCC secretariat produced a user manual[15] and a resource guide, both of which are available on the UNFCCC website.[16]

Table 6.1: Summary of GHG inventory reporting requirements under the UNFCCC

	Developed countries[17]	Developing countries[18]
Frequency	Submitted annually; summary included with national communication	Submitted with national communication (no set frequency); part of biennial reports starting in December 2014
Format	Electronic	NCs: Hard copy BURs: Electronic
Years covered	1990 (or other base year) to most recent year available	2nd NCs: 2000; BURs: 2010 (or more recent years if information is available) for the 1st BUR; subsequent BURs to cover a calendar year that does not precede the submission date by more than four years; time series back to the years reported in previous NCs encouraged
Gases	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 required	NCs and BURs: CO_2, CH_4, N_2O required; HFCs, PFCs, SF_6 encouraged
Sectoral	Summary tables and sectoral	NCs: Only summary tables are required

[15] The manual is available in English, French and Spanish.

[16] UNFCCC website: http://unfccc.int/resource/docs/publications/userman_nainc_en.pdf; http://unfccc.int/resource/docs/publications/09_resource_guide1.pdf; http://unfccc.int/resource/docs/publications/08_resource_guide2.pdf; http://unfccc.int/resource/docs/publications/09_resource_guide3.pdf; http://unfccc.int/resource/docs/publications/08_resource_guide4.pdf.

[17] Guidelines adopted in 2005 applied for the third, fourth and fifth national communications; separate guidelines for annual inventories updated in 2005 and were most recently revised during COP 17 (decision 15/CP.17), which also apply for biennial update reports.

[18] Guidelines adopted in 2002 applied for second national communications.

Disaggregation	background data tables required	BURs: Summary tables required; tables in annex 3A.2 to the IPCC good practice guidance for LULUCF and the sectoral report tables annexed to the Revised 1996 IPCC Guidelines encouraged
Version of the IPCC Guidelines	1996 Guidelines and Good Practice Guidance (2000 and LULUCF) required; 2006 Guidelines will be used for a trial period (October 2012 to May 2013)	NCs and BURs: 1996 Guidelines required; Good Practice Guidance (2000 and LULUCF) is encouraged
Documentation	Extensive documentation of methods and data sources required in a "national inventory report"	NCs: Encouraged to provide information on methods used BURs: Encouraged to provide information on methods used; additional or supporting information, including sector-specific information, may be supplied in a technical annex

Initial NCs were to include a GHG inventory for either 1994 or 1990, while second NCs were to include GHG inventory for 2000. To date, most developing countries have provided data for only one inventory year (1994 for most of them) in their initial NC. While developing countries are required to prepare their inventory using the Revised 1996 IPCC Guidelines (IPCC, 1996), the use of the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (GPG 2000) (IPCC, 2000) and GPG-LULUCF is encouraged. Providing documentation on the methodologies used to prepare the NCs is also encouraged but not required.

Reporting of estimates of GHG emissions and removals from all sectors is done through a table that is included in the reporting guidelines (reproduced in Figure 6.1). The requested information is very aggregate and not many countries followed the encouragement for the provision of more detailed information in the form of the IPCC worksheets and summary tables.

Figure 6.1: Reproduction of the reporting table for national communications of developing countries (source: http://unfccc.int/resource/docs/cop8/07a02.pdf#page=2)

Greenhouse gas source and sink categories	CO_2 emissions (Gg)	CO_2 removals (Gg)	CH_4 (Gg)	N_2O (Gg)	CO (Gg)	NO_x (Gg)	NMVOCs (Gg)	SO_x (Gg)
Total national emissions and removals	X	X	X	X	X	X	X	X
1. Energy	X	X	X	X	X	X	X	X
A. Fuel combustion (sectoral approach)	X		X	X	X	X	X	X
1. Energy industries	X		X	X	X	X	X	X
2. Manufacturing industries and construction	X		X	X	X	X	X	X
3. Transport	X		X	X	X	X	X	X
4. Other sectors	X		X	X	X	X	X	X
5. Other (please specify)	X		X	X	X	X	X	X
B. Fugitive emissions from fuels	X		X		X	X	X	X
1. Solid fuels			X		X	X	X	X
2. Oil and natural gas			X		X	X	X	X
2. Industrial processes	X	X	X	X	X	X	X	X
A. Mineral products	X				X	X	X	X
B. Chemical industry	X		X	X	X	X	X	X
C. Metal production	X		X	X	X	X	X	X
D. Other production	X				X	X	X	X
E. Production of halocarbons and sulphur hexafluoride								
F. Consumption of halocarbons and sulphur hexafluoride								
G. Other (please specify)	X		X	X	X	X	X	X
3. Solvent and other product use	X			X			X	
4. Agriculture			X	X	X	X	X	X
A. Enteric fermentation			X					
B. Manure management			X	X			X	
C. Rice cultivation			X				X	
D. Agricultural soils			X	X			X	
E. Prescribed burning of savannahs			X	X	X	X	X	
F. Field burning of agricultural residues			X	X	X	X	X	
G. Other (please specify)			X	X	X	X	X	
5. Land-use change and forestry	X[b]	X[b]	X	X	X	X	X	X
A. Changes in forest and other woody biomass stocks	X[b]	X[b]						
B. Forest and grassland conversion	X	X	X	X	X	X		
C. Abandonment of managed lands		X						
D. CO_2 emissions and removals from soil	X[b]	X[b]						
E. Other (please specify)	X	X	X	X	X	X		
6. Waste			X	X	X	X	X	X
A. Solid waste disposal on land			X		X		X	
B. Waste-water handling			X	X	X	X	X	
C. Waste incineration					X	X	X	X
D. Other (please specify)			X	X	X	X	X	X
7. Other (please specify)	X	X	X	X	X	X	X	X
Memo items								
International bunkers	X		X	X	X	X	X	X
Aviation	X		X	X	X	X	X	X
Marine	X		X	X	X	X	X	X
CO_2 emissions from biomass	X							

Note: Shaded cells do not require entries.

[a] The following standard indicators should be used, as appropriate, for emissions by sources and removals by sinks of GHGs: **NO** (not occurring) for activities or processes that do not occur for a particular gas or source/sink category within a country, **NE** (not estimated) for existing emissions and removals which have not been estimated, **NA** (not applicable) for activities in a given source/sink category which do not result in emissions or removals of a specific gas, **IE** (included elsewhere) for emissions and removals estimated but included elsewhere in the inventory (Parties should indicate where the emissions or removals have been included), **C** (confidential) for emissions and removals which could lead to the disclosure of confidential information.

[b] Do not provide an estimate of both CO_2 emissions and CO_2 removals. "Net" emissions (emissions – removals) of CO_2 should be estimated and a single number placed in either the CO_2 emissions or CO_2 removals column, as appropriate. Note that for the purposes of reporting, the signs for removals are always (–) and for emissions (+).

It should be noted that the revised guidelines were adopted before the finalization of the GPG-LULUCF. This resulted in reporting for forest-related activities that is based on the four categories of the Revised 1996 Guidelines (Changes in forest and other wood biomass stocks; Forest and grassland conversion; Abandonment of managed lands; CO_2 emissions and removals from soils). All developing countries followed this structure in reporting emissions and removals in their initial communications.

For the preparation of subsequent NCs, the UNFCCC Secretariat is providing training that includes information on how to incorporate elements of the GPG-LULUCF in the inventory process. As a result, it is anticipated that developing countries will start using the GPG-LULUCF for their future NCs. Specifically for reporting, this means that future NCs are likely to contain more detailed information, provided that countries use the reporting guidance of the GPG-LULUCF.

Biennial Update Reports

As part of the 2010 Cancun Agreements (Decision 1/CP.16 [UNFCCC, 2010], further elaborated by Decision 2/CP.17 [UNFCCC, 2011]) developed and developing countries are required to submit BURs containing information on GHG emissions and removals, as well as on mitigation actions, needs, and support received for the implementation of these actions. Access to this information will allow for the assessment of results of the implemented mitigation actions.

The reporting guidelines for BURs are contained in Annex III to Decision 2/CP.17 (UNFCCC, 2011). Specifically for LULUCF, Paragraph 6 of these guidelines states that, "Non-Annex I Parties are encouraged to include, as appropriate and to the extent that capacities permit, in the inventory section of the biennial update report, tables included in Annex 3A.2 to the IPCC good practice guidance for LULUCF…"

Nationally Appropriate Mitigation Actions

The Cancun Agreements, developed at COP 16, include two important decisions regarding mitigation actions that will be implemented by developing countries:

- Development of Nationally Appropriate Mitigation Actions (NAMAs) to deviate their emissions relative to business-as-usual emissions in 2020 in the context of sustainable development; and
- Collectively with developed countries, aim to slow, halt and reverse forest cover and carbon loss by implementing REDD+ activities.

NAMAs are to be formulated by developing countries based on their own national priorities and conditions, but can be funded by external/international donors and/or through the use of domestic resources. Internationally supported actions will be measured, reported and verified domestically and will also be subject to international MRV, while domestically supported mitigation actions will be measured, reported and verified domestically.

The purpose of NAMAs is to serve as a mitigation strategy for a developing country and REDD+ could be part of the overall NAMA strategy of a country. To be efficient, sufficient, and predictable, financial resources should provide appropriate incentives to the relevant actors at the right time, making it worthwhile for them to change their current behavior and use of resources. To do so, a system for Measurement, Reporting and Verification (MRV) of emissions and removals related to implemented actions is very important, and the cornerstone of such a system is a reliable national GHG inventory that is prepared following the IPCC principles (transparency, consistency, comparability, completeness and accuracy).

6.2.2 General guidance for reporting

While the content and timing for reporting of REDD+ activities under the UNFCCC has not yet been established, the Cancun Agreements noted the need to ensure consistency with the development of any guidance regarding MRV agreed for NAMAs. Both sections of the Cancun Agreement on NAMAs and REDD+ significantly change the legal requirements for reporting of developing countries under the UNFCCC.

For the future, it is expected that developing countries will have to move from a system based on temporary arrangements (designed to deliver national GHG inventories together with national communications without any time constraint) to a permanent system capable of delivering national GHG inventories and supplementary information at least every two years.

One of the recurring themes in the reporting of developing countries on REDD+ is the use of the GPG-LULUCF. According to this guidance, GHG-related information should be reported in an inventory of emissions and removals that is typically divided into two parts: reporting tables and an inventory report. In addition, the GPG-LULUCF contains worksheets that can be used to perform the actual calculations of emissions and removals and could be included in the inventory to improve transparency. In the sections below we will discuss these three elements.

Worksheets

The GPG-LULUCF contains worksheets, presented in different modules, with each module corresponding to a specific land-use category[19]. A module is divided into two sub-modules to distinguish between those lands that remain in the same land-use category and those lands converted to other land-use categories. Each sub-module is further divided into four worksheet groups covering: living biomass; dead organic matter; soils (further sub-grouped into mineral soils and organic soils); and non-carbon dioxide (CO_2) GHG emissions. While the worksheets are largely based on Tier 1 methods, they are supplemented with higher tier methods where appropriate.

In general, worksheets contain the following information:

- *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;
- A*ctivity data*. Areas of land, in thousands of hectares, subjected to gross deforestation, degradation and management of forests;
- *Emission factors*. Carbon-stock changes per unit area deforested or degraded or *managed*, separated for each carbon pool;
- *Total change in carbon stock*. Obtained by multiplying each activity data by the relevant emission carbon stock change factor; and
- *Total emissions*. Expressed in physical units (e.g., Gg) or in CO_2 equivalents.

An example of a compilation worksheet is shown in Figure 6.2.

[19] Example worksheet: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp3/Anx_3A_2_Reporting_Tables.pdf

Reporting tables

Two types of reporting tables are provided in the GPG-LULUCF. The first represents a matrix of the area of all land that was converted to another category and the associated emissions. Though this manual focuses on forest monitoring, this table is provided as an example. The second type of table is a subset of the first type, and results from the first table because it reflects the resultant change in carbon stock due to activities. It also reports the emissions and removals of CO_2 and non-CO_2 GHGs due to conversion of the six categories to any other land-use categories. All reporting tables are included in Annex A3.2 of the GPG-LULUCF.[20] For illustration, the summary reporting table is reproduced in Figure 6.3 (two parts).

To ensure the completeness of an inventory, it is important to fill in information for all entries of the reporting tables. If actual emission and removal quantities have not been estimated or cannot otherwise be reported in the tables, the inventory compiler should use qualitative "notation keys" provided by the IPCC Guidelines and GPG (see Table 6.2), along with supporting documentation. For example, if a country decides that a disproportionate amount of effort would be required to collect data for a pool from a specific category that is not a key category in terms of the overall level and trend in national emission, then the country should list all gases/pools excluded on these grounds, together with a justification for exclusion, and use the notation key "NE" (Not Estimated) in the reporting tables. Furthermore, the reporting tables are generally complemented by a documentation, which should be used to provide references to relevant sections of the inventory report if any additional information is needed.

Figure 6.2: Reproduction of a compilation worksheet for reporting emissions and removals

TABLE 3A.2.2A

COMPILATION WORKSHEETS FOR REPORTING CO_2 EMISSIONS AND REMOVALS [1]

Land-use Category [2]		Land Area	Living Biomass			Dead Organic Matter			Soils[3]		
Initial Land-use	Land-use during reporting Year	(ha)	Annual increase in carbon stocks (tonnes C yr^{-1})	Annual decrease in carbon stocks (tonnes C yr^{-1})	Annual change in carbon stocks (Gg CO_2 yr^{-1}) C = (A-B) • 10^{-3} • 44/12	Carbon stock change in dead wood (tonnes C yr^{-1})	Carbon stock change in litter (tonnes C yr^{-1})	Annual change in carbon stock (Gg CO_2 yr^{-1}) F = (D+E) • 10^{-3} • 44/12	Carbon stock change in mineral soils (tonnes C yr^{-1})	Carbon stock change in organic soils (tonnes C yr^{-1})	Annual change in carbon stock (Gg CO_2 yr^{-1}) I = (G+H) • 10^{-3} • 44/12
			A	B	C	D	E	F	G	H	I
Forest Land	Forest Land										
Cropland	Forest Land		ΔC_{LF_G} [4]	ΔC_{LF_L}	$\Delta C_{LF_{LB}}$	$\Delta C_{LF_{DW}}$	$\Delta C_{LF_{LT}}$	$\Delta C_{LF_{DOM}}$	$\Delta C_{LF_{Mineral}}$	$\Delta C_{LF_{Organic}}$	$\Delta C_{LF_{Soils}}$
Grassland	Forest Land										
Wetlands	Forest Land										
Settlements	Forest Land										
Other Land	Forest Land										
	Sub-total for Forest Land										
Cropland	Cropland										
Forest Land	Cropland										
Grassland	Cropland										
Wetlands	Cropland										
Settlements	Cropland										
Other Land	Cropland										
	Sub-total for Cropland										
Grassland	Grassland										
Forest Land	Grassland										
Cropland	Grassland										
Wetlands	Grassland										
Settlements	Grassland										
Other Land	Grassland										
	Sub-total for Grassland										
Wetlands	Wetlands										
Forest Land	Wetlands										
Cropland	Wetlands										
Grassland	Wetlands										
Settlements	Wetlands										
Other Land	Wetlands										
	Sub-total for Wetlands										

[20] http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp3/Anx_3A_2_Reporting_Tables.pdf

Other tables that may also be incorporated in a report include:

- Tables with emission trends, including data from previous inventory year; and
- Tables for illustrating the results of the key category analysis, the completeness of the reporting and eventual re-calculations.

A key category is one that is prioritized within a national inventory system because its estimate has a significant influence on a country's total inventory of GHG in terms of the absolute level of emissions and removals, the trend in emissions and removals, or uncertainty in emissions or removals. Whenever the term key category is used, it includes both source and sink categories.

Inventory report

The other part of a national inventory is an inventory report that contains comprehensive and transparent information. Typical sections of the inventory report are:

- 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. In the context of REDD+ reporting, appropriate information on land-use definitions, land area representation and land-use databases are likely to be required;
- A description of the key categories, including information on the level of category disaggregation used and its rationale, the methodology used for identifying key categories, and if necessary, explanations for why the IPCC-recommended tiers have not been applied;
- Information on uncertainties (i.e., methods used and underlying assumptions), time-series consistency, recalculations (with justification for providing new estimates), QA/QC procedures and archiving of data;
- A description of the institutional arrangements for inventory planning, preparation and management; and
- Information on planned improvements.

Table 6.2: Notation keys for use in GHG-reporting tables

Notation key	Explanation
NE (Not estimated)	Emissions and/or removals occur but have not been estimated or reported.
IE (Included elsewhere)	Emissions and/or removals for this activity of category are estimated but included elsewhere. In this case, indicate where they are located.
C (Confidential information)	Emissions and/or removals are aggregated and included elsewhere in the inventory because reporting at a disaggregated level could lead to disclosure of confidential information.
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.

Furthermore, all of the relevant inventory information should be compiled and archived, including all disaggregated emission factors, activity data and documentation on how these factors and data were generated and aggregated for reporting. This information should allow for reconstruction of the inventory by experts not involved in its preparation.

Figure 6.3: Reproduction of summary reporting tables

TABLE 3A.2.1A

REPORTING TABLE FOR EMISSIONS AND REMOVALS OF CO_2 AND NON-CO_2 GASES FROM LULUCF IN THE REPORTING YEAR

Land-use Category		*IPCC Guidelines* [1]	Annual change in carbon stocks, Gg CO_2				CH_4	N_2O	NO_x [3]	CO [3]
Initial Land-use	Land-use during reporting Year		Living Biomass A	Dead Organic Matter B	Soils C	CO_2 Emissions/ Removals [2] D = (A+B+C) • (-1) D	(Gg)	(Gg)	(Gg)	(Gg)
Forest Land	Forest Land	5A								
Cropland	Forest Land	5A, 5C, 5D	$\Delta C_{LF_{LB}}$ [5]	$\Delta C_{LF_{DOM}}$	$\Delta C_{LF_{SOM}}$					
Grassland	Forest Land	5A, 5C, 5D								
Wetlands	Forest Land	5A, 5C, 5D								
Settlements	Forest Land	5A, 5C, 5D								
Other Land	Forest Land	5A, 5C, 5D								
	Sub-Total for Forest Land									
Cropland	Cropland	5A, 5D								
Forest Land	Cropland	5B, 5D								
Grassland	Cropland	5B, 5D								
Wetlands	Cropland	5D								
Settlements	Cropland	5D								
Other Land	Cropland	5D								
	Sub-Total for Cropland									
Grassland	Grassland	5A, 5D								
Forest Land	Grassland	5B, 5D								
Cropland	Grassland	5C, 5D								
Wetlands	Grassland	5C, 5D								
Settlements	Grassland	5C, 5D								
Other Land	Grassland	5C, 5D								
	Sub-Total for Grassland									
Wetlands	Wetlands	5A, 5E								
Forest Land	Wetlands	5B								
Cropland	Wetlands	5E								
Grassland	Wetlands	5B								
Settlements	Wetlands	5E								
Other Land	Wetlands	5E								
	Sub-Total for Wetlands									

TABLE 3A.2.1A (CONTINUED)

REPORTING TABLE FOR EMISSIONS AND REMOVALS OF CO_2 AND NON-CO_2 GASES FROM LULUCF IN THE REPORTING YEAR

Land-use Category		*IPCC Guidelines* [1]	Annual change in carbon stocks, Gg CO_2				CH_4	N_2O	NO_x [3]	CO [3]
Initial Land-use	Land-use during reporting Year		Living Biomass A	Dead Organic Matter B	Soils C	CO_2 Emissions/ Removals [2] D = (A+B+C) • (-1) D	(Gg)	(Gg)	(Gg)	(Gg)
Settlements	Settlements	5A								
Forest Land	Settlements	5B								
Cropland	Settlements	5E								
Grassland	Settlements	5B								
Wetlands	Settlements	5E								
Other Land	Settlements	5E								
	Sub-Total for Settlements									
Other Land	Other Land	5A								
Forest Land	Other Land	5B								
Cropland	Other Land	5E								
Grassland	Other Land	5B								
Wetlands	Other Land	5E								
Settlements	Other Land	5E								
	Sub-Total for Other Land									
Other [4] (pls. specify)										
	Sub-Total for Other									
Total										

[1] Headings from the *IPCC Guidelines* Reporting Instructions p.1.14 - 1.16: 5A - Changes in Forest and Other Woody Biomass Stocks; 5B - Forest and Grassland Conversion; 5C - Abandonment of Managed Lands; 5D - Emissions and Removals from Soils, and 5E - Other.

[2] For the purpose of reporting, it is necessary to reverse the sign so that the resulting value is expressed as (-) for removal or uptake and (+) for emission. Thus, negative 1 is multiplied to the resulting CO_2 emission or removal.

[3] The *IPCC Guidelines* and this report provide methodology to estimate NO_x and CO emissions for Land Use, Land-Use Change and Forestry for emissions from fires only. If you have reported additional data, you should provide additional information (method, activity data, and emission factors) used to make these estimates.

[4] This may include other non-specified sources or sinks such as HWP, etc.

[5] Symbols are provided to show the relationship among the worksheets, compilation worksheets, reporting table, and the equations in the main body of the report. Please note that symbols are provided for only one land-use category as an example.

Software for reporting

The UNFCCC provides software, which has been developed using Microsoft Excel, where activity data (AD) and emission/removal factors data can be input to obtain net annual carbon uptake/release. There are several key features or limitations in using the software, such as:

- The names or type of forest/plantation category in a country may differ from the categories defined in the UNFCCC software;
- The UNFCCC software can be changed to nationally relevant categories (e.g., Acacia species can be changed to another species);
- Names of categories used in the column are not included in the calculation procedure of the worksheets and thus can be easily changed; and
- Forest/plantation categories: Option exists for 18 categories, which is a limitation if a country has more than 18 categories. There are two options if the number of forest/plantation categories is more than provided: i) Insert additional rows only if the inventory expert has capacity to modify the "macros"; or ii) merge smaller or homogeneous categories such that the total number of rows (or categories) is not larger than 18.

The IPCC task force on GHG Inventory released a revised version of the software in April 2013 (v2.11) to help countries estimate and report GHG emissions and removals; this software is compatible with the 2006 IPCC Guidelines (IPCC, 2006).

As an alternative to the UNFCCC software, one could use the Agriculture and Land Use GHG Inventory Software[21] which guides inventory compilers through the process of estimating GHG emissions and removals related to agricultural and forestry activities (ALU Software, 2013). The software simplifies the process of conducting the inventory by dividing the inventory analysis into steps to facilitate the compilation of activity data, assignment of emission factors and completion of the calculations. The software also has internal checks to ensure data integrity. Many governments also have an interest in mitigating GHG emissions from agriculture and forestry. Determining mitigation potential requires an understanding of both current emission trends and the influence of alternative land use and management practices on future emissions.

6.3 VERIFICATION

Verification for REDD+ is an issue that is being negotiated at the international level under the auspices of the UNFCCC. The next session of the COP will take place in November 2013 in Warsaw. At that session, it is anticipated that verification requirements and procedures for REDD+ will be agreed upon. The implications of the outcome of meeting in Warsaw will be reflected in the next version of this manual. Without prejudice to the outcome of the UNFCCC negotiations, the information contained in this version of the manual originates from section 5.7 of the GPG-LULUCF in order to provide a stand-alone document that is as complete as possible. The elements taken from the GPG-LULUCF are those most relevant to REDD+ activities in the opinion of the authors. In some instances, text is quoted verbatim from the IPCC document, in other instances changes have been made to reflect specific REDD+ aspects. Previous negotiations have also included discussions on other elements that should be verified. For example, some

[21] http://www.nrel.colostate.edu/projects/ALUsoftware/index.html.

parties want to include the development of a verification process for reference levels and reference emission levels; other discussions have focused on issues such as transparency, in terms of how monitoring systems address deforestation.

According to the GPG-LULUCF, the "purpose of verifying national GHG inventories is to establish their reliability and to check the accuracy of the reported numbers by independent means. Verification can be performed at several levels: project, national and international."

The IPCC has also stipulated that the overall goals of verification are to provide inputs to improve GHG inventories, build confidence on estimates and trends, and to help to improve scientific understanding. These goals can be achieved through:

- Internal checks, which are performed by the organizations, agencies or individuals that are responsible for the compilation of the inventory; and
- External checks, which are performed by other bodies not directly involved with the preparation of the GHG inventory (e.g., other government agencies, private companies, research consortiums, independent scientists, non- governmental organizations).

The uniqueness of the estimation methods for forestry-related activities has led to the conclusion that verification "would be based on complete accounting of emissions and removals at the national scale, measured by independent methods at different levels, and possibly complemented by top-down approaches based on atmospheric measurements." A complete verification process would require cross-checking of the results at different scales (sub-national and national), depending on a country's national circumstances.

At the same time, the IPCC has recognized that "such verification would be complex and resource intensive, and possibly performed by research consortiums and/or programs" .Furthermore, "cross-checking requires considerable time and it is likely to be implemented over multiple years, rather than on a single year basis."

6.3.1 Approaches to verification

Review or third-party verification of information submitted by developing countries under the UNFCCC has been a contentious issue in the negotiations. As a result, there is no agreed review process under the UNFCCC that would apply to developing countries. At COP 17, governments agreed on an international consultation and analysis (ICA) process for BURs by developing countries as a means to assess submitted information. A brief overview of the ICA is given below in sub-section "External verification" of 6.3.2. However, the five main approaches to verification currently included in the GPG-LULUCF are listed below, though these verification approaches may be modified based on UNFCCC negotiations.

1) Comparison to other information, such as independent inventories and international programs and datasets;
2) Application of higher tier methods;
3) Direct measurement of emissions and removals of GHGs;
4) Remote sensing; and
5) Using models.

Although there is no consensus on verification approaches, in addition to the above five approaches the following may be included: peer and public review; examination of specific aspects of the inventory, such as underlying data (collection, transcription, and analysis); emission factors; activity data assumptions; rules used for the calculations (suitability and application of methods, including models); and upscaling procedures. No matter which verification approaches are used or what aspects of the inventory are verified, it is important to

keep in mind that verification should be conducted using data and methods that are independent from those used to prepare the inventory.

The criteria for selecting verification approaches include: scale of interest, costs, desired level of accuracy and precision, complexity of design and implementation of the verification approaches, and the required level of expertise needed to verify.

For each approach, a technical description is given in Section 5.7 of the GPG-LULUCF[22] with reference to its applicability (e.g., for a particular category, types of data). The IPCC guidance also provides a table that contains information to assist in identifying the most suitable approaches for particular categories or inputs (Figure 6.4).

[22] http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp5/Chp5_7_Verification.pdf

Figure 6.4: Reproduction of the table for general applicability of verification approaches

TABLE 5.7.1
APPLICABILITY OF VERIFICATION APPROACHES FOR LAND AREA IDENTIFICATION AND FOR CARBON POOLS AND NON-CO_2 GREENHOUSE GASES

	Approach 1 **Comparison with other inventories and other independent datasets**	**Approach 2** **Applying higher tier methods**	**Approach 3** **Direct measurement**	**Approach 4** **Remote sensing**	**Approach 5** **Modelling**
Land area	Suitable, if data are available	Suitable, if data are available	Not applicable	Suitable	Not applicable
Carbon pools					
Aboveground biomass	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable (ground data needed)	Suitable (regression, ecosystem and growth models)
Belowground biomass	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable, (regression, ecosystem and growth models)
Dead wood	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Applicable (ecosystem and inventory-based models)
Litter	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Applicable (ecosystem and inventory-based models)
Soil organic matter	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem and inventory-based models)
Non-CO_2 greenhouse gases	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem models)
Emission factors	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem models)
Activity/land-based report					
Forest, grassland, cropland, other land uses	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable, particularly to identify land cover/land use and their changes	Suitable, Data-intensive, Can be an alternative approach when estimates from direct measurements and remote sensing are not available
Afforestation, Reforestation, Deforestation, projects	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable, particularly to identify land cover/land use and their changes	Not practical

6.3.2 General guidance for verification

According to the GPG- LULUCF, there are two key considerations for an inventory agency in its efforts to develop a verification plan:

- **Identify the criteria for selecting the inventory elements for verification**. For example, key source/sink categories should be given priority for verification. At the same time, non-key categories can also be selected for verification if they are of particular relevance to mitigation efforts, or their uncertainty is high or they are expected to change significantly over the inventory reporting period.
- **Decide how the inventory elements will be verified**. In addition to the suitability/availability of a particular verification approach, other criteria to be used for selecting a particular approach include: the type of data to be verified; the spatial scale of the inventory coverage; the quantity and quality of the data to be verified; and the accuracy, precision and cost of the approach itself.

Internal verification

The GPG-LULUCF stipulates that "if a country undertakes internal verification of its inventory, it should ensure that:

- Sufficient independent expertise is available;
- Documentation of the verification is included in the inventory report;
- Uncertainty estimates and QA/QC documentation is included in the report;
- Other available national verification activities are described;
- Applied verification methods are transparent, rigorous and scientifically sound;
- Verification results are reasonable and well-explained; and
- Final calculations can be reasonably linked to underlying data and assumption."

Some of the checks and comparisons that can be used for internal verification of the LULUCF sector are summarized in Box 5.7.3[23] of the GPG-LULUCF (reproduced below). These checks and comparison are essential, and ideally they should have been conducted as a part of QA/QC.

[23] http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp5/Chp5_7_Verification.pdf

Figure 6.5: Box 5.7.3 of the GPG LULUCF

BOX 5.7.3
VERIFICATION OF INVENTORY OF LULUCF SECTOR IN A NATIONAL INVENTORY

A. Checks:

Does the inventory of the LULUCF sector document the data and assumptions used for estimating emissions and removals for all IPCC source/sink categories?

Have all important carbon pools been included in the inventory?

If some LULUCF emission/removal categories have been omitted, does the report explain why?

Are emissions and removals reported as *positive* and *negative* terms, respectively?

For the total area of the inventory of the LULUCF sector, are the overall changes in land-use for the inventory year equal to zero within the confidence limit?

Are any discontinuities in trends from base year to end year evaluated and explained?

B. Comparisons of emissions and removals from LULUCF:

Compare the inventory of the LULUCF sector with independently prepared national inventories for the **same** country or compare regional sub-sets of the national inventory with independently prepared inventories for those regions. (Table 5.7.1, Approach 1).

Compare the inventory of the LULUCF sector with national inventories for a **different**, but similar country (Table 5.7.1, Approach 1).

Compare activity data and/or emission factors of the inventory of the LULUCF sector with independent international databases and/or other countries. For example, compare Biomass Expansion Factors of similar species with data from countries with similar forest conditions (Table 5.7.1, Approach 1).

Compare the inventory of the LULUCF sector with results calculated using another tier methodology, including defaults (Table 5.7.1, Approach 2).

Compare the inventory of the LULUCF sector with available high-intensity studies and experiments (Table 5.7.1, Approach 1-3).

Compare land areas and biomass stocks used in the inventory with remote sensing (Table 5.7.1, Approach 4).

Compare the inventory of the LULUCF sector with models (Table 5.7.1, Approach 5).

C. Comparisons of uncertainties:

Compare uncertainty estimates with uncertainty reported in the literature.

Compare uncertainty estimates with those from other countries and the IPCC default values.

D. Direct measurements:

Carry out direct measurements (such as local forest inventory, detailed growth measurements and/or ecosystem fluxes of greenhouse gases, Table 5.7.1, Approach 3).

Country-specific circumstances and availability of resources are key to selecting appropriate verification approaches. In general, "Approaches 1, 2 and 3 are feasible for verifying several components of the inventory. Approaches 1 and 2 can be easily implemented by an inventory agency with low to moderate resources. Remote sensing is the most suitable method for the verification of land areas. Direct measurements are relevant, although this approach can be resource-intensive, and, on a large scale, costs may

be a constraint. Models can be used as an alternative when direct measurements combined with remote sensing is not feasible."

External verification

An example of a type of an external verification is the international consultation and analysis (ICA), which is a process that has been agreed upon under the UNFCCC and will apply to BURs of developing countries. The first rounds of ICA will be conducted for developing countries, commencing within six months of the submission of the first round of biennial update reports.

The aim of the ICA is to increase the transparency of mitigation actions and their effects through analysis by technical experts in consultation with the countries concerned and through a facilitative sharing of views. This will ultimately result in a summary report. The ICA will be conducted in a manner that is non-intrusive, non-punitive and respectful of national sovereignty.

The ICA process will consist of the following two steps:

1) A technical analysis of the BUR by a team of experts in consultation with the country, and will result in a summary report. The information considered includes the national GHG inventory report, information on mitigation actions, including a description of such actions, an analysis of their impacts and the associated methodologies and assumptions, the progress made in their implementation, information on domestic measurement, reporting and verification, and on support received.

2) A facilitative sharing of views, which will have as input the BURs and the summary report referred to above.

The country concerned may provide additional technical information. Prior to finalizing the report, the draft summary report prepared by the team of technical experts will be shared with the country concerned for review and comment over the following three months in order to respond to and incorporate Party comments in the report.

6.4 REFERENCES

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7.0 THEMATIC REVIEWS

7.1 HISTORY OF REDD+ UNDER THE UNFCCC

Author: Angel Parra

7.1.1 Introduction

This thematic review provides an overview of negotiations on reducing emissions from deforestation and forest degradation (REDD+) under the United Nations Framework Convention on Climate Change (UNFCCC) and the role that the Intergovernmental Panel on Climate Change (IPCC) has played in providing methodological guidance to Land Use, Land-Use Change and Forestry (LULUCF). This review provides additional context, whereas the current reporting guidance under the UNFCCC is discussed in Chapter 6.

Informed decision-making and successful implementation of international agreements on climate change (such as the UNFCCC and its Kyoto Protocol) rely on the availability of accurate and reliable information on greenhouse gas (GHG) emissions and removals. The realization by the international community of the urgency to address REDD+ has prompted decisions that emphasize the importance of Masurement, Rporting and Vrification (MRV) of GHG emissions and removals as well as their role in global mitigation efforts to address the impacts of anthropogenic climate change.

According to the decisions adopted by governments working under the aegis of the Conference of the Parties (COP) to the UNFCCC, developing countries willing to take action on REDD+ have to establish a national forest monitoring system to assess anthropogenic forest-related GHG emissions by sources and removals by sinks. As REDD+ actions should be results-based, developing countries will have to demonstrate that they are reducing emissions from deforestation, compared to a business-as-usual scenario, or reference emission levels (RELs).

7.1.2 Overview of REDD+ negotiations under the UNFCCC

Forestry has been recognized as one of the key sectors to be addressed in the broader context of GHG mitigation under the UNFCCC. The principle of "common but differentiated responsibilities" of the Convention (1992), Article 4, paragraph 1 (c) stipulates that all countries must "promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of GHGs not controlled by the Montreal Protocol in all relevant sectors, including the energy, transport, industry, agriculture, forestry and waste management sectors."

Also included in Article 4 are commitments for all countries to "promote sustainable management, and promote and cooperate in the conservation and enhancement of sinks and reservoirs of all GHGs not included in the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems" (Article 4, paragraph 1 (d).

The complexity of the sector, however, has posed a number of challenges, which have postponed decisions on how to address the reduction of GHG emissions from forestry activities, especially in developing countries.

This dynamic changed at the 11th Meeting of the COP (COP11) in Montreal, Canada in 2005, when Papua New Guinea and Costa Rica, with support from eight other countries proposed a mechanism for reducing emissions from deforestation in developing countries. The proposal received wide support and the COP began a two year process to explore options for REDD with the participation of both governments and observer organizations submitting proposals and recommendations on how to reduce GHG emissions from deforestation and forest degradation.

At COP13, governments agreed on the Bali Road Map that defined broader scope for future global action. The Bali Action Plan (Decision 1/CP.13) signaled the beginning of a new global process through long-term cooperative action on all aspects of climate change, namely mitigation, adaptation, technology and finance. A key element of the international negotiations was the role of developing countries in national and international efforts to mitigate climate change. The Bali Action Plan included considerations on the following actions:

- Nationally appropriate mitigation actions (NAMAs) by developing country Parties in the context of sustainable development, supported and enabled by technology, financing and capacity-building, in a measurable, reportable and verifiable manner (sub-paragraph 1 (b) (ii) of Decision 1/CP.13); and
- 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 (sub-paragraph 1 (b) (iii) of Decision 1/CP.13).

These provisions bring together national mitigation efforts, REDD+, sustainable development, technology, finance and MRV. Initiating negotiations on future action, however, does not mean that current mitigation efforts should be discounted, or discontinued as the negotiations process is to be informed by "… the best available scientific information, experience in implementation of the Convention and its Kyoto Protocol, and processes there under, outputs from other relevant intergovernmental processes and insights from the business and research communities and civil society."[24] The intention is that lessons learned from current efforts will guide the intergovernmental process as it defines a new way forward.

COP13 also adopted Decision 2/CP.13 on "reducing emissions from deforestation in developing countries: approaches to stimulate action." Through this decision, the COP encouraged capacity-building activities, technical assistance, the facilitation of technology transfer and the development of demonstration activities. The decision also requested advancement of relevant methodological work by the Subsidiary Body for Scientific and Technological Advice (SBSTA).[25]

One year later, at COP14 in Poznań, Poland in 2008, the SBSTA reached agreement on a number of issues relating to REDD+, including:

- The organization of an experts meeting on: methodological issues relating to RELs for deforestation and degradation; the relationship among the RELs and other relevant reference levels (RLs); and the role of conservation, sustainable management of forests, changes in forest cover and associated carbon stocks and GHG emissions and the enhancement of forest carbon stocks to enhance action on climate change mitigation;

[24] Paragraph 11 of Decision 1/Cp.13

[25] The SBSTA is a permanent subsidiary body under the UNFCCC process. It supports the work of the COP and the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (CMP) through the provision of timely information and advice on scientific and technological matters as they relate to the Convention and the Kyoto Protocol.

- A recommendation on methodological guidance noting the importance of, inter alia, promoting readiness of developing countries, and further mobilization of resources, in relation to decision 2/CP.13, as well as recognizing the need to promote the full and effective participation of indigenous people and local communities, taking into account national circumstances and noting relevant international agreements; and

- A recommendation on the use of the Revised 1996 IPCC Guidelines for National GHG Inventories, and encouragement to use the IPCC Good Practice Guidance for LULUCF (GPG-LULUCF), as appropriate.

It is important to note that in climate negotiations, the terms RL and REL refer to a reference level or baseline that can be developed by taking into account historic data. These terms have not been defined by the UNFCCC or IPCC, and while sometimes used interchangeably they usually differ in use. RLs refer to the amount of emissions from deforestation and forest degradation and the amount of removals from sustainable management of forests and enhancement of forest carbon stocks. RELs refer only to the amount of emissions from deforestation and forest degradation.

Significant progress was made in REDD+ negotiations leading up to COP15 in Copenhagen, Denmark in 2009. Despite the difficulties in reaching agreement on an overall package as a result of COP15, the negotiations on REDD+ culminated in the adoption of Decision 4/CP.15 which addressed issues such as scope, guiding principles, safeguards and a phased approach to REDD+. Specifically, through Decision 4/CP.15, the COP, among other things:

- Requested developing countries to, inter alia, identify drivers of deforestation and forest degradation, and to use the most recent IPCC guidance to estimate emissions and establish national forest monitoring systems;

- Encouraged capacity-building support from all able parties for capacity building in developing countries;

- Encouraged development of guidance for indigenous peoples and local community engagement;

- Recognized that forest RELs should take into account historic data, and adjust for national circumstances; and

- Urged coordination of efforts.

The outcome of COP16 in Cancun, Mexico in 2010 was a milestone for REDD+ because many of the key decisions adopted at previous sessions (Bali, Poznan and Copenhagen) were consolidated as part of the Cancun Agreements (Decision 1/CP.16). In particular, the COP affirmed that, provided adequate and predictable support is forthcoming, developing countries should aim to slow, halt and reverse forest cover and carbon loss. The COP also encouraged developing country parties to contribute to mitigation actions in the forest sector through actions in the five specific areas listed in Box 7.1.

Developing countries were requested to develop a national strategy or action plan, national forest RLs or sub-national RLs as an interim measure, a robust and transparent national forest monitoring system and a system for providing information on how the safeguards listed in Appendix I to Decision 1/CP.16 (see Box 7.2) would be addressed throughout implementation.

The COP also requested the SBSTA to develop a work program to identify, among other issues, drivers of deforestation and degradation, and methodologies for estimating emissions and removals from these activities. The work program was to develop modalities for MRV of emissions by sources and removals by sinks resulting from these activities, consistent with MRV of NAMAs for consideration at COP18. The Ad-Hoc Working Group on Long-Term Cooperative Action was requested to explore financing options for the full implementation of results-based actions and to report on this at COP17.

Following the successful outcome of Cancun, governments continued to work throughout 2011 in preparation for COP17 in Durban, South Africa in 2011. Earlier in the year, at the SBSTA34 meeting in Bonn, Germany, work continued on technical guidance for MRV, including principles that should be followed when designing MRV systems; these discussions have continued at subsequent SBSTAs. .

The negotiations during COP17 focused on two groups of issues relating to REDD+:

- Sources of financing for REDD+, the role of markets and non-markets and the potential use of offsets; and
- Guidance on systems for providing information on how safeguards are addressed and respected, modalities for forest RELs and RLs and MRV.
- As part of the outcome of COP17 (Decision 2/CP.17), the COP agreed, among other things:
- Regardless of the source or type of financing, the activities referred to in paragraph 70 of Decision 1/CP.16 (see Box 7.1) should be consistent with the relevant provisions included in Decision 1/CP.16, including the safeguards in its Appendix I (see Box 7.2);
- Results-based finance provided to developing countries that is new, additional and predictable may come from a wide variety of sources, including public and private, bilateral and multilateral; and
- In light of the experience gained from current and future demonstration activities, appropriate market-based approaches could be developed by the COP to support results-based actions in developing countries.

Box 7.1: Paragraph 70 of Decision 1/CP.16

The Conference of the Parties,

…

70. Encourages developing country Parties to contribute to mitigation actions in the forest sector by undertaking the following activities, as deemed appropriate by each Party and in accordance with their respective capabilities and national circumstances:

(a) Reducing emissions from deforestation;

(b) Reducing emissions from forest degradation;

(c) Conservation of forest carbon stocks;

(d) Sustainable management of forests;

(e) Enhancement of forest carbon stocks;

In Decision 12/CP.17, the COP noted that guidance on systems for providing information on safeguards should be consistent with national sovereignty, national legislation and national circumstances. Under the section on guidance on these systems for providing information on how safeguards are addressed and respected, the COP, *inter alia*:

- Noted that the implementation of safeguards and information on how these safeguards are being addressed and respected should support national strategies or action plans and be included in all phases of implementation, where appropriate;
- Agreed that the systems for providing information on how the safeguards are addressed and respected should, among other things: provide transparent and consistent information that is accessible by all relevant stakeholders and updated on a regular basis, be country-driven and implemented at the country level, and build upon existing systems, as appropriate;
- Agreed that developing countries undertaking the activities referred, should provide a summary of information on how the safeguards referred to are being addressed and respected throughout the implementation of the activities;
- Decided that the summary of information referred to should be provided periodically and included in national communications, consistent with relevant COP decisions on non-Annex I Parties' national communications, or communication channels agreed by the COP; and
- Requested SBSTA 36 to consider the timing of the first presentation and the frequency of subsequent presentations of the summary of information to be considered by COP18, and the need for further guidance to the COP.

Box 7.2: Safeguards for REDD+ activities (paragraph 2 of Appendix I to Decision 1/CP.16)

2. When undertaking the activities referred to in paragraph 70 of Decision 1/CP.16, the following safeguards should be promoted and supported:

(a) That actions complement or are consistent with the objectives of national forest programmes and relevant international conventions and agreements;

(b) Transparent and effective national forest governance structures, taking into account national legislation and sovereignty;

(c) Respect for the knowledge and rights of indigenous peoples and members of local communities, by taking into account relevant international obligations, national circumstances and laws, and noting that the United Nations General Assembly has adopted the United Nations Declaration on the Rights of Indigenous Peoples;

(d) The full and effective participation of relevant stakeholders, in particular indigenous peoples and local communities, in the actions referred to in paragraphs 70 and 72 of Decision 1/CP.16;

(e) That actions are consistent with the conservation of natural forests and biological diversity, ensuring that the actions referred to in paragraph 70 of Decision 1/CP.16 are not used for the conversion of natural forests, but are instead used to incentivize the protection and conservation of natural forests and their ecosystem services, and to enhance other social and environmental benefits;[1]

(f) Actions to address the risks of reversals;

(g) Actions to reduce displacement of emissions.

(1) Taking into account the need for sustainable livelihoods of indigenous peoples and local communities and their interdependence on forests in most countries, reflected in the United Nations Declaration on the Rights of Indigenous Peoples, as well as the International Mother Earth Day.

Under modalities for RELs and RLs, the COP, inter alia:

- Agreed that RELs and/or RLs are benchmarks for assessing each country's performance in implementing the referred activities;
- Decided that these shall be established considering Decision 4/CP.15, paragraph 7 and consistent with anthropogenic forest-related GHG emissions by sources and removals by sinks in a country's GHG inventories;
- Invited developing countries to submit information and rationale on the development of their RELs and/or RLs including details of national circumstances, and if adjusted to national circumstances, including details in accordance with the guidelines contained in the annex to Decision 2/CP.17 (see Box 7.3);
- Acknowledged that sub-national RELs and/or RLs may be elaborated as an interim measure, while transitioning to a national level, and that interim reference levels may cover less than the national territory of forest area;
- Agreed that developing countries should update RELs and/or RLs periodically, as appropriate, taking into account new knowledge, trends and any modification of scope and methodologies; and
- Agreed to a process enabling technical assessment of the proposed RLs when submitted or updated by parties in accordance with guidance to be developed by SBSTA 36.

The UNFCCC has also addressed countries' needs to set RELs. RELs or RLs represent benchmarks for assessing a country's performance in implementing REDD+ activities. Countries implementing REDD+ activities under the UNFCCC will need to develop their RELs and submit them to the UNFCCC. The emissions estimates from these will then be compared with those estimated via MRV, and the difference between the two will be used to measure the effectiveness of each country's policies and measures related to REDD+.

The first UNFCCC guidance on RELs was provided in Decision 4/CP.15, which recognized that RELs should be established transparently, should take into account historical trends, yet could be adjusted for national circumstances. Decision 1/CP.16 then defined RELs/RLs as one of the elements Parties aiming to undertake REDD+ activities should develop, in accordance with national circumstances, and that sub-national RELs could be used as an interim measure. The most recent guidance on RELs emerged from COP17, indicating that Parties should: i) establish RELs maintaining consistency with forest emissions and removals as contained in countries' national GHG inventories; ii) submit information/rationale on the development of their RELs, including how national circumstances were considered; iii) consider a step-wise approach to the development of RELs to enable the incorporation of improved data and methodologies; and iv) update RELs periodically to account for new knowledge and trends. The cumulative guidance indicates that RELs should be developed with strong links to the design of the national MRV system, ensuring consistency in the approaches to the collection and use of data.

7.1.3 Methodological work of the IPCC on GHG inventories

IPCC is a scientific body of the United Nations that was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization. Its mandate is to provide the world with a clear scientific view on the current state of climate change knowledge and its potential environmental and socio-economic impacts. To do this, the IPCC reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide. It does not conduct any research nor does it monitor climate related data or parameters.

To accomplish its work, the IPCC is organized into three working groups (WGs) responsible for assessing: the Physical Science Basis (WG1); the Climate Change Impacts, Adaptation and Vulnerability (WG2); and the Mitigation of Climate Change (WG3). A schematic on the structure of the IPCC is shown in Figure 7.1. Other ad-hoc task groups and steering groups may be established to consider specific topics or questions.

In addition to the three WGs, the IPCC has established the Task Force on National GHG Inventories to oversee the IPCC National GHG Inventories Program (NGGIP). Its core activity is to develop and refine internationally agreed methodologies and a software program for the calculation and reporting of national GHG emissions and removals, and to encourage its use by countries participating in the IPCC and by the Parties to the UNFCCC. The NGGIP also established and maintains the IPCC Emission Factor Database (EFDB) discussed in Chapter 3.

7.1.4 History of IPCC methodological guidelines and guidance

Since its inception in the early 1990s, the IPCC has played a key role in the development of methodological guidelines and guidance that, over the years, have become the cornerstone for all work on GHG inventories. Specifically:

- In November 1994, the IPCC approved the first version of the IPCC Guidelines for National GHG Inventories. This was the first internationally accepted methodology that became the basis for the development of national GHG inventories under the UNFCCC;
- The Revised 1996 IPCC Guidelines for National GHG Inventories include revised methodologies and default data for six main sectors: Energy; Industrial Processes; Solvents and Other Product Use; Agriculture; LULUCF; and Waste. In addition, methodologies were included for the estimation of halofluorocarbons, perfluorinated hydrocarbons, sulphur hexafluoride, ozone and aerosol precursors, and direct GHG (CO2, methane [CH4], nitrogen dioxide [N2O]);
- In response to requests by the UNFCCC, the IPCC developed the Good Practice Guidance and Uncertainty Management in National GHG Inventories (GPG 2000), which addressed all sectors mentioned above except for land-use change and forestry and the GPG-LULUCF in 2000 and 2003, respectively. These two documents do not replace, but supplement the information in the Revised 1996 Guidelines and provide good practice guidance on choice of estimation methodology, improvements of the methods, as well as advice on cross-cutting issues, including estimation of uncertainties, time series consistency and quality assurance and quality control (QA/QC).
- The 2006 IPCC Guidelines on National GHG Inventories are an evolutionary development starting from the Revised 1996 Guidelines, the GPG 2000, and the GPG-LULUCF. The most significant changes occur in Volume 4, which consolidates the approach to LULUCF in GPG-LULUCF and the Agriculture sector in GPG2000 into a single Agriculture, Forestry and Other Land Use (AFOLU) Volume.

Box 7.3: Guidelines for submissions of information on reference levels(Annex to decision 12/CP.17)

Each developing country Party aiming to undertake the actions listed in decision 1/CP.16, paragraph 70, should include in its submission information that is transparent, complete[(1)], consistent with guidance agreed by the Conference of the Parties (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 Intergovernmental Panel on Climate Change guidance and guidelines, as adopted or encouraged by the COP, as appropriate, and include:

(a) Information that was used by Parties in constructing a forest reference emission level and/or forest reference level, including historical data, in a comprehensive and transparent way;

(b) Transparent, complete, consistent and accurate information, including methodological information, used at the time of construction of forest reference emission levels and/or forest reference levels, 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;

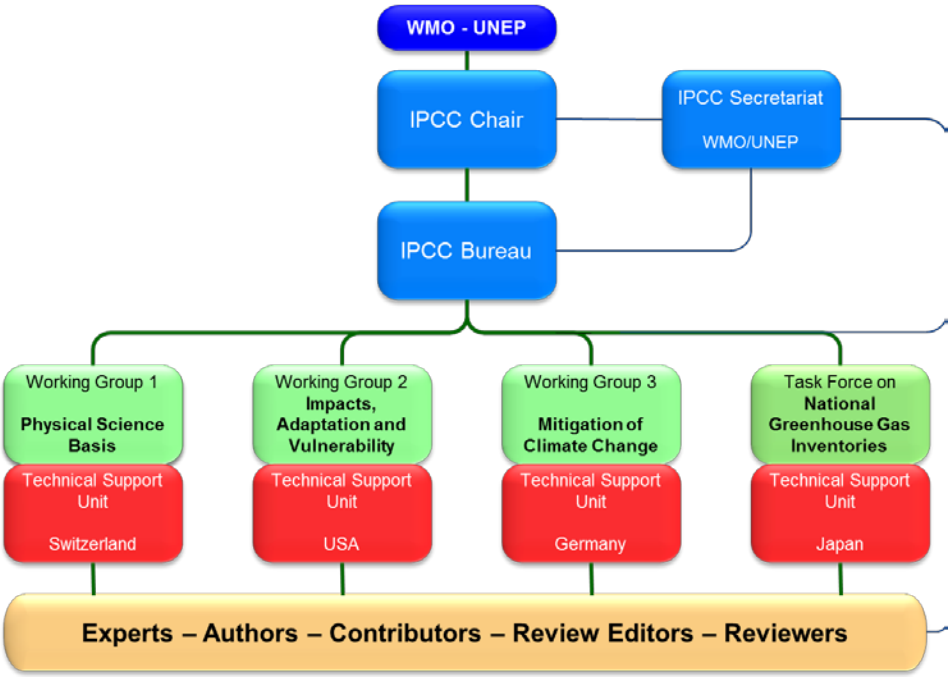
(c) Pools and gases, and activities listed in decision 1/CP.16, paragraph 70, which have been included in forest reference emission levels and/or forest reference levels and the reasons for omitting a pool and/or activity from the construction of forest reference emission levels and/or forest reference levels, noting that significant pools and/or activities should not be excluded;

(d) The definition of forest used in the construction of forest reference emission levels and/or forest reference levels and, if appropriate, in case there is a difference with the definition of forest used in the national greenhouse gas inventory or in reporting to other international organizations, an explanation of why and how the definition used in the construction of forest reference emission levels and/or forest reference levels was chosen.

(1) Complete here means the provision of information that allows for the reconstruction of forest reference emission levels and/or forest reference levels.

The LULUCF sector has evolved significantly between the Revised 1996 Guidelines and the 2006 IPCC Guidelines (see Figure 3.1). These changes are a result of better understanding of the sector and the availability of more scientific research.

Figure 7.1: IPCC structure and functions (source: IPCC TFI)



7.1.5 Other non-UN processes

In addition to countries' preparing for national implementation of REDD+, advances have been made at the sub-national level in the context of voluntary carbon markets and bilateral agreements. Sub-national implementation has mostly been at the site level. However, there has been some progress at the sub-national jurisdiction level. In some cases, site-level activities are being developed within jurisdictions that are also developing their own broader REDD+ strategies. This requires the development of a "nested" approach to REDD+ strategies, accounting of emission reductions and distribution of emissions-reduction credits.

These sub-national REDD+ efforts look to separate groups to provide guidance on setting reference levels and aspects of MRV. Two groups providing guidance are the Voluntary Carbon Standards group (VCS) and the American Carbon Registry (ACR) (ACR, 2013; VCS, 2013). Both have provided technical methodologies recommended for sub-national REDD+ reference levels and MRV. These tend to defer to the IPCC where possible, for example in carbon-stock assessments and fundamental concerns such as transparency and replicability. Both efforts seek to align with existing UNFCCC guidance on REDD+ and are intended to follow and support additional UNFCCC REDD+ guidance as it emerges. These efforts have also helped provide guidance on how to approach issues particular to jurisdictional and nested REDD+.

For example, within the guidance of both the VCS and the ACR, a jurisdiction is any politically defined region delineated for the purposes of tracking carbon stocks, deforestation rates and GHG reductions through REDD+ project activities. A jurisdiction may be a national or sub-national political entity (nation, state, province, district, etc.), though other ways of defining jurisdictional boundaries are also possible. A nested REDD+ project is one that is accounted and monitored in reference to the jurisdictional accounting framework (baseline, leakage assessment, monitoring requirements) in which the project takes place. This can have the benefit of reducing transaction costs for projects, allowing them to use the baseline and other requirements developed by the jurisdiction, rather than having to develop these at the project level, while also helping to attract private capital for REDD+.

7.1.6 References

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7.2 COMMUNITY-BASED MONITORING

Authors: Kemen Austin and Fred Stolle

The objective of this thematic review is to highlight the potential benefits and required processes for incorporating community-based monitoring into a national REDD+ monitoring initiative. We examine relevant literature and case studies of community-based monitoring of biodiversity, water quality, and forest biomass, in order to identify common challenges and lessons for REDD+.

7.2.1 Definition of community-based monitoring

According to Fernandez-Gimenez et al (2008), "Community-based monitoring implies the direct involvement of community members in monitoring, either through their participation in collaborative monitoring efforts, or by training and contracting community members to carry out monitoring projects". In this review, a community member is defined as a resident in or near an area of interest, and differentiates community members from external consultants who live in another city, province, or country. Additionally, this study recognizes that community-based monitoring can be initiated by community members to evaluate community initiatives such as forest management, or by external entities to evaluate larger landscape or regional-scale projects.

Community-based monitoring has been used to examine a number of forest elements including biodiversity, carbon stocks, cultural and religious points of interest, illegal extraction rates and timber and non-timber products (Effah 2011). Additionally it is broadly recognized that REDD+, as well as many other domestic policy initiatives, will require monitoring of non-carbon elements such as social safeguards (UNFCCC 2010). These may include land tenure conflicts, respect for human rights, benefit sharing, and mechanisms to ensure participation. This review focuses principally on how communities can participate in the collection of biophysical data, while acknowledging other areas in which community members can contribute valuable information.

7.2.2 Community-based monitoring in the context of REDD+

As discussed in earlier chapters, the range of MRV systems and forest monitoring systems that are being developed for REDD+ will likely require monitoring of forest changes, forest carbon stocks, and 'safeguards' for biodiversity conservation and livelihood support (Danielsen et al 2010).

Community-based monitoring can be incorporated into these monitoring systems, and the role of indigenous peoples and local communities is explicitly referred to in the UNFCCC Cancun Agreement (UNFCCC 2010). However, the mechanisms by which communities will be involved in forest monitoring have not received much attention in the UNFCCC context. The potential roles that community-based monitoring can contribute to a national REDD+ monitoring system are outlined in Table 7.1, below.

Table 7.1: Potential role for community-based monitoring in national monitoring systems (adapted from Pratihast and Herold 2011)

Component of Monitoring System	Monitoring Options at the National Level	Potential Contribution of Community- Based Monitoring
Forest Mapping and Stratification	Map forests based on biophysical indicators and some broad management regimes	Map forests based on community tenure or site specific management
Monitoring deforestation and reforestation	Conduct remote sensing Carry out national forest inventory Collect data from forestry companies Calibrate or validate satellite imagery with field crews	Observe the location, time, area and type of change events (in near real time) Collect regular measurements on the ground in near real time Calibrate or validate satellite imagery
Monitoring degradation, enhancement of forest carbon stocks	Analyze historical data if available Conduct surveys on fuelwood and non-timber forest product (NTFP) use Carry out national forest inventory	Collect regular ground level measurements of forest carbon stocks
Estimation of emission factors	Deploy field crews to collect data Rely on research projects	Collect field data regularly over time
Identification of drivers of change	Make inferences regarding patterns of change and likely cause	Track types and patterns of local activities that cause change Map tenure, management and land-use plans
Data analysis and reporting	Collect and standardize data from national and sub-national sources Provide data to the public	Submit data to national entity Use data for local purposes

7.2.3 Rationale for community-based monitoring for REDD+

While remote sensing is considered the most promising method for national scale assessments of forest change (Patenaude et al 2005, Defries 2007, GOFC-GOLD 2009), limitations exist, as discussed in Chapter 4, which will require the use of many ground-based methods to accurately report on emissions from forest change, and emission reductions from a REDD+ program. Remote sensing-based methods will need to be supplemented with a range of local level monitoring for calibration and validation (Schellas et al. 2010) to develop emission factors and collect information on social and cultural indicators.

Reliability

The use of international teams of specialized personnel in the collection of ground-based data represents an expensive process, and approaches that involve local people can reduce costs, increase frequency of monitoring, provide benefits such as training and salaries, and facilitate the collection of information on difficult-to-observe metrics. This section further explains the rationale for employing community-based monitoring.

Recent studies have used community members and external consultants to quantify forest carbon stocks to compare the accuracy of community-based monitoring against a 'best practice' alternative (Van Laake 2011). Results from 30 projects in 7 countries demonstrate that there is no significant difference in the accuracy between these two groups, once the community members have been trained in the required methods (Van Laake 2011).

However, these studies also estimate that data collected by community members can have higher variability and lower precision than data collected by external counterparts experienced in forest inventories (Skutch and McCall 2011). This may be the result of the participating community members having expert knowledge of their own environment and resources, but generally less sophisticated data collection expertise (Skutch and McCall 2011).

Cost Effectiveness

Forest monitoring is one of the largest costs associated with REDD+ in developing countries and, therefore, identifying ways to reduce costs is vital (Skutsch et al 2011). A study by Larazzabal and Skutsch (2011) estimated the costs of community-based monitoring to be one-third to half the cost of monitoring conducted by external consultants (including training costs). Other studies estimate that in the long run, costs of community-based monitoring are much lower compared to the costs associated with travel and salaries for external consultants (Rist 2010, Topp-Jorgensen 2005, Danielsen et al (2010). However, the monitoring costs depend on many factors including the frequency and scale of monitoring and the opportunity costs for monitors.

Importantly, many of the costs associated with community monitoring occur in the initial stages of the project or initiative (Effah 2011). These costs include purchasing of equipment, setting up permanent sample plots, and training. Therefore, because these costs are constant and independent of the size or timeframe of the project, community monitoring is most cost effective for larger areas and projects that aim to monitor over at least several years (Effah 2011). One study suggests that a minimum size of 100 hectares is required to break even, relative to the transaction costs of setting up a community monitoring system (Danielsen et al 2010).

Frequency

Forest monitoring for REDD+ will require more than a one-off assessment. Rather, information will need to be collected regularly at intervals appropriate for the forest type and management regime. Community members located in and around areas of interest are well positioned to monitor over longer periods of time and with higher frequency than several other options, such as a national forest service entity or visiting technical consultants (Rist 2010). More frequent monitoring of forest conditions and changes can improve the statistical and scientific reliability of the resulting data, particularly in forests undergoing rapid change (Danielsen et al 2010).

Sensitivity to local context

Community members can have detailed knowledge of their local surroundings including an awareness of small scale variations in management (Dalle 2006). Additionally, community members are often knowledgeable regarding drivers of local forest changes (Van Laake 2011). As a result, communities are well

positioned to observe the impacts of human use on forest and forest carbon and gauge the influence of management or policy implementation.

Understanding of social and cultural impacts

The success of REDD+ will depend on both accurate and transparent forest monitoring of carbon emissions and removals and on non-carbon elements such as the safeguards outlined in the Cancun Agreements (UNFCCC 2010). Community members are well positioned to collect information on a broader range of metrics beyond carbon that may be needed for potential REDD+ or national forest management policy implementation (Pratihast and Herold 2011). These metrics include socio-economic information (e.g., biomass energy use, food production), governance (e.g., benefit sharing processes, mechanisms for participation in decision making), and biodiversity (e.g., species observations, habitat changes).

Provision of benefits to communities

Involving local community members in forest monitoring can lead to additional benefits such as increased ownership of mitigation actions, improved cultural relevance of monitoring approaches, strengthened capacity of local institutions, access to resources, and employment opportunities (Danielson 2010). Thus, participation of community members can lead to the long-term sustainability of interventions and of monitoring initiatives. Table 7.2 discusses the comparative advantage of local communities in forest monitoring projects.

Table 7.2: Advantages and disadvantages of community-based and expert-based monitoring (from Knowles et al 2010, adapted from Larrazabal and Skutch 2011)

Monitoring Component	External Consultants	Local Community Members
Costs	High; includes professional fees, travel and accommodation costs	High initial set-up and training costs followed by relatively lower salary, travel and accommodation costs over time
Local Knowledge	Usually poor; local guides and translators usually needed	Good; residents typically know the area well in terms of access, logistics, local authorities, laws and species
Data Quality	Good	Good; dependent on appropriate training and data verification
Consistency	Potentially low if the same consultants cannot continue monitoring over the lifespan of the project, or the same methods are not adhered to	Potentially high if the same team members, or at least the same coordination, can be maintained
Frequency and Intensity	Usually low; it is very costly for external experts to spend long periods in the field, or return to carry out measurements frequently over time	High; even if sampling is done part-time, substantial travel and set-up time is saved and monitoring can be carried out frequently
Additional benefits	Low; usually limited to technical input	High; monitoring by locals creates ownership, adds to the capacity of local residents, and offers opportunities to improve management
Management	Expected to be good	Potential areas of concern in many communities
Initial training	Low; assumes that professional teams need little preparation	High; takes more time to identify, train and equip teams
Collection of other data	Generally poor; very challenging to understand local socio-economy and culture, time consuming to collect the data	Good; built-in knowledge of local economy and culture, easy to collect information and monitor changes

7.2.4 Lessons from case studies

This section presents a synthesis of cases in which communities have been involved in forest monitoring, either for REDD+, or for other metrics that might be relevant to a REDD+ program. In addition, the common challenges and lessons for scaling up to the national level are discussed. The cases are also summarized in Table 7.3.

Locally driven versus externally driven monitoring

Several of the studies examined the application of community-based monitoring where a community had set up (or was in the process of setting up) a system for managing common forest resources (Topp-Jorgensen 2004, Mukama 2012, Hartanto 2002). In this case, monitoring is used as a mechanism to track the performance of the management initiatives; this is also referred to as autonomous local monitoring (Danielsen et al 2008). The scope of local monitoring initiatives is tailored to local priorities and is usually not as in-depth as will be required for REDD+ monitoring (McCall 2003). However, community-based monitoring could, with the right incentives and training, be extended to include collaborative monitoring of carbon stocks and fluxes that contribute to externally driven REDD+ requirements (Lawrence and Elphick 2002).

There are also cases where community-based monitoring is initiated for national inventories or national research purposes (Skutsch and Trines 2011). This type of monitoring has also been termed "micro-macro monitoring" (Ojha et al 2003) and "externally driven monitoring with local data collection" (Danielsen et al 2008). Examples include the event-book system in Namibia (Stuart Hill 2005) and bird censuses in Kenya (Bennun 2005). This type of monitoring will be important for REDD+, which will require monitoring forest area gain, loss, and stock change over large landscapes (Skutsch and Solis 2011). However, in the case where community members are not already actively engaged in forest management, sufficient upfront resources and training may be necessary to effectively establish a community-based monitoring system.

Standards and Protocols

Monitoring for REDD+ will necessitate consistent and comparable data collection across sub-national jurisdictions. To achieve robust and consistent data collection, clear standards and protocols must be developed that local communities can easily learn and implement. Stuart-Hill et al (2005) present an example highlighting the successful harmonization of scaling up data collection. The authors present a case from Namibia where communities were provided adaptable but standardized data collection guidance. As participating communities used the same methods, the data could be aggregated and compared nationally.

Capacity building

The literature on community-based monitoring demonstrates that community members can reliably collect data on forests once basic training is provided. This training may include forest inventory methods, data recording, and use of equipment (e.g. maps, Global Positioning System (GPS) units, cameras). The Kyoto: Think Global, Act Local (K:TGAL) research and capacity building program, for example, found that training can take place over a short period of time; even one week of field-based training can be sufficient to collect data for forest inventories (Skutsch 2009).

A review of literature by Effah et al (2011) suggests that a phased approach to community monitoring may be most effective. Such a system would first build participant's capacity for forest monitoring, through intensive training and 'learning by doing' in which external consultants demonstrate principles and tasks to community members. Consultants can then continue supervision and support of more challenging tasks, such as statistical sampling, using complex computer equipment, and setting up permanent sample plots (Skutsch and Trines 2011).

Incentives

Community-based monitoring is unlikely to be sustainable unless the benefits of participating in a monitoring program outweigh the costs (Skutsch et al 2011). External support in the form of salaries and skill building for employment will be necessary to incentivize forest monitoring (Evans and Guariguata 2008, Rist et al 2010). The case studies examined here provided between $1 and $7 per day to participants. However only two of the studies addressed whether these costs were sufficient to overcome the opportunity costs of lost wages, and both found that the amount provided were not sufficient (Andrianandrasana 2005, Mukama 2012). This indicates that existing payment structures may not be sufficient to support community-based monitoring in the long-term.

Technical systems and equipment

All of the case studies examined employed some form of advanced technology such as GPS or computer software for collecting and storing data. McCall (2011) argues that these technologies put local knowledge 'on par' with knowledge from outside experts. Benefits of using these systems include increased accuracy, reduced data loss, systematic data collection, simplification of validation, capture of media such as photos or audio, skill development of participants, and easy data sharing (Fry 2011).

Depending on the circumstances of the study area, such as access to electricity and internet or comfort level of community members with sophisticated software platform, different approaches regarding the use of advanced technologies can be used. For example, the Socio Bosque program in Ecuador addresses the issue of exposure to GPS-enabled cell phones by grouping forest guards, hunters, and a mix of youth and elders chosen by the community into monitoring teams. By including a cross section of the community, the respective knowledge and strengths of each participant are shared amongst the group. Forest guards are comfortable with the technology, younger participants more readily learned to use these systems, and elders and hunters have more experience with species identification and in-depth historical knowledge (Cerda 2012).

Quality assessment and control

In order to incorporate forest monitoring into a national GHG inventory and reporting system, a quality control system should be put in place to assess the accuracy of data collected by local community members. For example, in the Scolel Tè project in Mexico, 10 percent of community-based monitoring is verified by project technical staff. If inconsistencies or inaccuracies are identified, additional training is provided (Scolel Tè 2008).

Data management and aggregation systems

In order for data from local monitoring systems to be useful at larger geographic scales, a database system is needed that will enable data acquired at a local level to be uploaded and shared (Pratihast and Herold 2011). Effah et al (2011) found that many projects demonstrate successful aggregation of data across sub-national jurisdictions into a central database. The Sofala Community Carbon Project in Mozambique, for example, will feed data on forest carbon stocks into Mozambique's national GHG inventory (Envirotrade 2010).

Additionally, data management systems should be designed to ensure that data collected by local community members is securely managed, and how the information collected will be used is clearly defined (CIGA-REDD 2011). Further, data needs to be retained by community members so that they can use it in their own decision-making processes (Stuart-Hill et al 2005). Data is frequently sent "upward" to be analyzed and used for management, but the results of this analysis and its broader implications are not communicated clearly to communities (Ojha et al 2003). Providing feedback knowledge will contribute to planning, allow communities to assess tradeoffs between alternative forest uses, and enable the evaluation of management impacts on forest resources.

Three key messages are apparent. First, recent research has demonstrated that data collected via community-based monitoring can be as reliable and policy relevant as data collected by external technical consultants. In

addition, monitoring carried out by community members enables and supports their participation in developing and implementing national REDD+ strategies, an explicit mandate of the Cancun Agreements (stated in Paragraph 72). Finally, community-based monitoring can contribute to a REDD+ MRV system at the national level. But to do so, the system must be supported by appropriate incentives, standards, data aggregation systems, and capacity building.

7.2.5 References

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Table 7.3: Case studies of community monitoring

Case Study	Location	What information was gathered?	Who conducted the monitoring?	What standards were used?	What equipment was used?	What training was provided to participants?	What incentives were provided to monitors?	Who conducted data compiling and analysis?	How was data aggregated at the national or regional level?	What was the cost of project?	Summary
Holck 2008	Uluguru North Forest Reserve, Tanzania	Tree diameter at breast height, basal area, disturbance (determined by burns, cuts, stumps)	Four elected participants from each village (two members of village environment committee, two members of WCS Tanzania)	Three methods of monitoring flora disturbance- the 20-tress methods, the Bitterlich gauge method and the Disturbance Checklist transect	Measuring tapes, pen and paper, Bitterlich gauge, ropes	Half-day and full day training and some follow-up supervision	Participants received approximately $6.25 per day, additionally participation conferred knowledge and prestige	Study authors	No aggregation	Once training has been done, costs for monitoring forest disturbance are estimated to be between $0.04 - $0.12/ha/yr.	Participants with full day training and supervision collected data similar to 'expert' counterparts. costs of local monitoring would enable more frequent and sustainable data collection
Topp-Jorgensen 2004	Iringa District, Tanzania	Resource use, disturbance, abundance of indicator species, information on resource use, records of user permits and fees, records of meetings and trainings	Village Natural Resource Committees	Locally developed protocols	Not specified	Guidance in developing system provided by the District government and the Danish Assistance Program	Monitors paid ~ $1/day. Other incentives include recognition of the value for water quality and increased prestige.	Village Natural Resource Committees	Monitoring data and local management decisions were reported monthly to higher administrative levels, and all records are kept publically available at the village	Estimated $3 million for the entire project- not specified which portion of this went to setting up the monitoring system	Village Natural Resource Committees managed monitoring and data analysis, and as a result were able to rapidly turn around quick management decisions based on this information

Danielson 2000	Three protected areas- Northern Sierra Madre, Bataan, M. Kitangl ad- Philippines	Change in number and frequency of sightings of listed designated species and resource use, change in size of vegetation types, change in perceived harvest volume in biodiversity impacting activities	Between 24 - 36 staff per park including the park superintendent, host NGOs, local forest guards and community members	Multiple methods developed- field diary, photo documentation, transect walk, focus group discussions. Standards and methods were developed through national collaborative process and field testing. A manual for each field method and indicator was prepared.	Notebook, pen, field guide, binoculars, camera, compass, film, altimeter, GPS, paint, watch, data sheets, string, tape measure	Capacity built over a period of three years. Stakeholders involved in the development and testing of methodologies. Regular visits by outside experts were made for assistance and supervision	Salaries were paid to park staff, amount not specified	All park staff are involved in compiling the data. The head of the protected area gathers and analyzes the data, and directly makes management decisions based on this result	The system for monitoring protected areas was being scaled to other priority protected areas at the time of writing.	Not specified	Important that the staff responsible for monitoring are different from those responsible for enforcement (in order to engage local communities effectively). Involvement of park staff throughout the development and testing of methodologies is key to buy in and long term capacity
Andriandrasana 2005	Alaotra wetlands, Madagascar	Data on lemurs, waterbirds, fish catches, march areas, and hunting rates	Organized by Durrell Wildlife Conservation Trust. Teams of 10 villagers and 7 technicians (from regional water and forest services, fishery service, and development NGOs)	Data collected via transects, interviews, catch observations, and species observation and identification. Standard methods were used across the 16 sites	Canoe, maps, binoculars, GPS, compass, bird field guide, weighing scales, site management plans, lemur field guide	Monitoring participants are trained upfront and then employed again in subsequent years. No further detail on the type of content of training provided	Participants earned ~ $2/day. This is less than income from fishing- may have been attractive because the employment conferred special status as a technical expert	The information was presented to the general public through community meetings and on the radio	Monitoring data presented orally to the public and data sheets kept by local authorities.	All costs approximately $5,000/yr. ($0.21/ha/yr.)	Local authorities demonstrated adaptive response to information collected- for example marsh fires were reduced over the course of the project.

Bennun 2005	49 sites in Kenya	Effectiveness of IBA conservation areas via monitoring of populations of relevant species and threats to these species (including habitat area, deforestation, number of conservation staff)	Bird Life 'Site Support Group' staff- local autonomous partners of Bird Life International made up of government staff and 'other knowledgeable individuals'	IBAs provide forms with indicator (e.g. habitat quality, number of conservation staff) and space for scoring improvement or deterioration in that indicator. Additionally, detailed site-specific monitoring encouraged, where method varied by site	Not specified	Not specified	Not specified- some financial support provided to site support groups from Bird Life International	Central IBA unit compiles data, checks it, and adds other research to develop an overall score of improvement or deterioration of indicators	Bird Life International develops national IBA status reports using data from each IBA. Additionally Bird Life International forwards the country report to the international secretariat to compile in a world database.	Not specified	This method is subjective and difficult to standardize, something that Bird Life has recognized and is working to improve.
Poulsen 2005	Xe Pian Biodiversity Conservation Area, Laos	Walk through focusing on list of priority species, villager interviews to determine perceptions of status and trends in hunted wildlife species and non-timber forest products, joint monitoring by villagers and protect area staff	Depending on the method teams of 2-6 villagers selected during village meeting, and protected area staff	Wildlife Conservation Society established, together with conservation area staff and villagers, a monitoring method, though standards were not strictly enforced and three main methods were used.	Not specified	Conservation area staff were trained in biodiversity monitoring and awareness raising, and can use the main monitoring methods	Conservation area staff paid annual salary, external support provided for logistics and field allowances of $5 per day. Villagers were not paid Monitoring stopped once external funding stopped.	Monitoring forms and reports filed at the Park Management Unit's office	Not specified	A week of monitoring, including 4-5 villages, costs approximately $100. This equivalent to approximately $0.017/ha/yr.	A combination of various methods may be the best way to get a holistic representation of resource use and abundance. Strong relationships between villagers and park staff builds trust, leading to cooperation and improved co-management.

Noss 2005	Kaa-Iya del Gran Chaco National Park, Bolivia	Species abundance, catch per unit effort rates, catch size, weight and age	Wildlife Conservation Society organized and supported the project in collaboration with Park administration. Active hunters and community members conducted monitoring.	Hunters carry data sheets with them on hunting excursions to record information. Community members also carry out line transect surveys of nine principal game species.	Data sheets, pens, tape measures, spring scales. GPS used to record hunting locations	Training is provided, details not specified	Hunters initially participated on volunteer basis, after 6 months the program hired 7-10 individuals on a part time basis in each community.	Community monitors analyze data monthly and summarize data every 6-12 months. Community meetings held to present the results and discuss possible interventions	Study authors use data to extrapolate from the number of hunters participating to the total number of hunters in the park	Approximately $50,000 per year for salaries, supplies and transportation costs ($0.015/ha/yr.)	
Mukama 2012	Three villages within the Angai Villages Land Forest Reserve, Tanzania	Participator forest mapping, forest transect walks to stratify forest into vegetation types, permanent sample plots to measure biomass in trees over time	Eight villagers were selected in each community	Participatory Rural Appraisal to map forest area, group discussions to gauge communities willingness to be involved,	Forest inventory equipment including diameter taps, tape measures, calipers, relascopes, GPS, hypsometers, also gumboots, transportation.	Participatory rural appraisal and focus group discussion methods were used to introduce concepts and research objectives, and gauge interest. Training was provided on using GPS, establishing permanent sample plots, forest inventory methods, use of equipment	Approximately $4/day (this was not seen as sufficient to cover opportunity costs of participants- community members proposed ~ $15/day for future work)	Calculations of tree volume and biomass using locally derived or generalized allometric equations completed by study authors	Not specified	$0.56 - $0.84/ha/monitoring event	Challenges included using GPS to mark vegetation strata boundaries, calculating sample size requirements, and determining transect and permanent sample plot locations. Some of these challenges could have been due to the short training time allocated. Successful implementation will depend on collaboration between local communities and facilitating organizations for GIS and carbon data analysis.

Hartanto 2002	San Rafael Tanabag and Concepcion Multipurpose Cooperative, Philippines	Information on social and environmental criteria, including education quality, income sources, strengthened organizations, and forest and coastal management,	Monitoring framework developed during three workshops and discussions with local people's organization, village council representatives, and department of environment and natural resources officials. Local people's organizations conducted monitoring.	Indicators developed for each criteria, for example number of pupils in school via school reports, monthly income via surveys, financial reports via organization record books, and number of trees via data reports	Not specified- varied by type of data collection	Participants involved in developing criteria and indicators, so awareness is high and methods in line with existing capabilities	Not specified	Monitoring results shared through monthly meetings, quarterly newsletters, community bulletin boards. More training needed to gauge success of management	Not specified- primary goal is to feedback data to local communities, so aggregation not prioritized	Not specified	Wide range of required indicator data highlights needs for highly varied skill set for data collection
Stuart-Hill 2005	30 community conservancies in six national parks, Namibia	Protocols for monitoring 21 themes have been developed, including for example rainfall, events of fire, poaching, wildlife mortalities, fish or predator abundance, etc., depending on community priorities	Field staff (conservancies members)	The communities involved decided what indicators to monitor (via community workshops), standards for monitoring 21 standard themes have been developed and kits containing tools for data collection, reporting and analysis of long term trends are made available to local communities	All forms are paper-based, and copied for archival in a storage box.	Training is provided on data collection and reporting	Not specified	All data compilation and analysis is conducted by local communities. Each year totals are transferred to a form to evaluate long-term trends. Community rangers collect data, report this to natural resource supervisors, who in turn report to conservancy manager or elected chairman.	Each year the data from each community is copied to a national monitoring and evaluation database belonging to the Ministry of Environment and Tourism and used for strategic decision making such as quota setting, allocation of technical support, or compliance monitoring.	Not specified	Traditionally there were long time lags before the results of data analysis was returned to communities, and the graphs and tables were not intuitively understood by community members. Where monitoring is driven by local priorities it may not be comprehensive; where society deems other indicators worth monitoring appropriate incentives must be provided.

7.3 NEAR-REAL TIME MONITORING AND ALERT SYSTEMS

Author: John Musinsky

7.3.1 Introduction

Near real-time (NRT) forest monitoring involves tracking forest threats or disturbances in such a way as to minimize the lag time between monitoring observations and the dissemination of critical information necessary for responding and intervening to reduce the impacts of detected threats. By enabling a rapid response to deforestation, degradation, wildfire, and potentially other phenomena "in-action", NRT forest monitoring can strengthen enforcement and governance at local levels. NRT alerts facilitate distribution of information in a streamlined user-customized form that can help overcome communication bottlenecks. Such monitoring increases transparency and deters future activities that contribute to forest loss or degradation. NRT forest monitoring and alerts, combined with community-based monitoring, facilitates effective forest management while ensuring respect for local customs and rights. Satellite and mobile technologies are also continually evolving, bringing new opportunities for employing multiple streams of NRT forest monitoring data for decision support and use in MRV systems.

NRT monitoring is not a requirement for national GHG reporting or inclusion in a national MRV system. However, there are significant benefits that can come from the application of NRT within a monitoring system. This need not be part of the data generated to produce quantitative estimates of forest cover and GHG emissions, but represents an additional monitoring component, coordinated with a more traditional MRV system, that enables more efficient enforcement and governance, and more rapid adjustment of REDD+ strategies to changing circumstances. There is also much potential for linking NRT monitoring with community-based monitoring and community-based management, where communities either receive NRT information to act upon or contribute to NRT monitoring via analysis or confirmation. Most countries are not taking advantage of the possibilities of NRT within their national forest management and monitoring strategies. This section summarizes some of the more advanced satellite-based NRT applications and provides case studies.

7.3.2 Background

Remote sensing-based NRT forest monitoring and alert systems are among the most underutilized tools for helping manage and protect forest resources. A range of publically available satellite data resources exist that can be adapted to near real-time analysis and reporting, providing a platform for NRT surveillance of forest resources. NRT forest monitoring complements the periodic remote sensing-based analysis of forest extent and change conducted as part of MRV. It provides an effective project implementation and adaptive management tool for responding to the direct threats to forests, thus ensuring as much forest carbon is protected as possible.

In addition to the direct support NRT forest monitoring provides to rapid response and enforcement, it can have additional, indirect benefits for REDD+ activities. Public access to NRT information on the existence and rate of expansion of a deforestation or forest degradation activity increases transparency about the effectiveness of institutions responsible for controlling such activity, thus strengthening public pressure for improved governance and reform. Knowledge that illegal forest activity can be tracked almost real-time helps deter future illegal activity when those involved realize that their assumed difficult-to-monitor practices can, in fact, be monitored and interdicted. Further, repeated NRT alerts that track and report on patterns of new deforestation, encroachment, fire and logging throughout the year help institutions design management plans that accommodate the intra and inter-annual variability in spatial and temporal patterns of fire and associated deforestation and illegal logging activity. Finally, NRT forest monitoring helps address issues of sustainable

commodity value chains by providing timely information highlighting the supply chain of commercial crops such as palm oil.

7.3.3 Near real-time forest monitoring technologies

There are a range of existing and planned satellite technologies that are uniquely suited to providing NRT information due to their spatial and temporal characteristics. Optical remote sensing data are generally more suitable for NRT monitoring than RADAR or LiDAR data because: i) moderately trained remote sensing analysts can more readily detect and interpret changes to forest extent and structure when using optical data; ii) the individual image footprints from optical instruments are generally larger and have a shorter re-visit time, resulting in regular and more frequent image availability; iii) the image archives are spatially and temporally more complete; and 4) these data are generally cheaper.

Both RADAR and LiDAR data have unique attributes that may make them useful for NRT monitoring in certain circumstances including a RADAR instrument's ability to see through clouds, a major advantage in perennially cloud-covered areas, and the forest structure information provided by both RADAR and LiDAR instruments, which can be useful when monitoring subtle changes due to forest degradation. However, the technical challenges inherent in processing and interpreting RADAR data, the lack of frequent acquisition or comprehensive spatial coverage of LiDAR data, and the high cost of both RADAR and LiDAR mean these are generally not practical as NRT data sources.

Most satellite imagery used for forest monitoring in the tropics is acquired by sensors onboard polar-orbiting satellites such as Landsat, CBERS, Terra and Aqua, of which the latter two carry the MODIS instrument as a payload. And, while polar-orbiting satellites (orbiting at an altitude of less than 1000km) provide a cost-effective approach to gathering comprehensive, planet-wide imagery, one disadvantage of polar-orbiting satellites for NRT monitoring is the resultant temporal gaps in the data record. This is particularly true for instruments such as Landsat, CBERS, etc., with higher spatial resolutions, but lower temporal resolutions. An alternate source of NRT remote sensing data are geostationary satellites (satellites that hover continually over the same point on the ground as the earth revolves, providing uninterrupted observations of the ground) but, to maintain their geosynchronous orbits, most geostationary satellites are located at an altitude of around 35,000km. This results in a coarse pixel resolution that limits their utility for monitoring of small-scale forest disturbance like slash-and-burn deforestation or degradation. Geostationary satellite data are nevertheless useful for NRT detection of fires due to the thermal sensitivities of the detectors, and future geostationary satellites (e.g., GOES-R, FY-4) with 1km *visible* and *near-infrared* bands may be more suitable for uninterrupted NRT monitoring of moderate-scale forest activity.

7.3.4 Technical considerations for NRT monitoring systems

Effective NRT monitoring depends on the following conditions: i access to frequent or continuous contaminant-free/cloud-free data for both automated and manual NRT monitoring systems; ii) data with adequate spatial resolution to enable the direct detection of a forest disturbance activity in-progress (e.g. fire), or the indirect detection of disturbance post-activity in terms of altered physical forest structure or biomass lost; iii) minimal lag time between the disturbance and detection to enable effective action; and iv) if the monitoring represents part of a field-based response or enforcement, that the geographical precision of the data are sufficient to enable ground-based personnel to navigate to the specific location where the disturbance occurred. As part of this process, NRT monitoring data may be validated using independent, field-based information to determine its accuracy. Each condition is discussed in detail below.

Cloud-free data

Cloud contamination represents one of the biggest challenges in using optical satellite imagery for NRT forest monitoring. To compensate for excessive cloud contamination or temporal gaps in the data records of high-resolution satellite data, alternative data acquisition and processing strategies may be used. For example, co-analysis may be performed using multiple data sources (such as Landsat with ASTER, CBERS or SPOT) over the same geographical area and time frame. However, care must be used when co-analyzing multiple data sources with different spatial resolutions as certain small-scale activities may be detected in higher resolution data but not lower resolution data. If, for example, recently acquired higher resolution data are co-analyzed against older, lower-resolution data, "false-positive" detections may result from what appears to be new activity that is, in fact, older disturbance.

Spatial resolution

The spatial resolution of the satellite data must match the scale of the specific activity contributing to deforestation or forest degradation. It generally requires nine pixels (3x3) to accurately delineate features on the ground, though smaller-scale disturbances to canopy cover are sometimes detectable with 2x2 pixel arrangements when there is a strong contrast between adjacent land-cover types (e.g., bare soil and green vegetation). A 15m resolution pan-sharpened Landsat image can be used to detect moderate-scale forest activities like slash-and-burn agriculture on the order of 0.25-0.50 hectares, and a 30m, i.e., non-pan-sharpened, Landsat image can be used to classify patches of deforestation 0.75 hectares and larger. Small-scale forest activities such as selective logging, crown removal and establishment of skid trails require very high resolution satellite data, such as SPOT-5 (5m pan), IKONOS (1m pan), Quickbird (0.7m pan) or GeoEye-1 (0.5m pan).

The relationship between pixel-size and an observed phenomenon is somewhat different for the detection of active fires. Thermal channels on many earth-observing satellite platforms are designed to accurately detect the large amounts of thermal radiation (heat) emitted from ground-fires. These thermal bands have pixels that cover much larger areas than the fires they are able to detect due to the contextual relationship of the fire location compared to the background area. For example, field studies have shown that the 1km resolution thermal bands on MODIS are able to accurately detect open ground fires covering an area of only $50m^2$.

Latency

To effectively contribute to field-based responses to undesirable or illegal forest activity, including the deployment of environmental law enforcement officials or the coordination of community-based monitoring personnel, the satellite data used to detect the specific types of activity must be acquired, interpreted, and reported with minimal time delay. The delay between satellite observation and product delivery to users is termed latency. NASA's Near Real Time Processing Effort for Earth Observation System products utilizes data with very short latencies, on the order of two to three hours for MODIS data (O'Neal, 2005). In contrast, Landsat averages approximately two days between image acquisition and distribution, while ASTER scenes are only available to the user seven to ten days after acquisition. In addition to the satellite data latency, a time lag often exists between the forest activity occurrence and the moment of satellite observation. This time lag may be minimal, for example a maximum of four hours when using MODIS data to monitor fires, or up to 21 days when using Landsat to monitor deforestation. In practice, however, the lag time may be substantially longer due to interference from cloud cover. Cloud cover effectively extends the functional time lag far beyond the theoretical minimal time lag. Finally, a lag time exists during the image analysis phase to detect new forest activity occurrences, and distribution of these data to end-users. This lag time may be very short when employing automated analytical processing systems, or considerably longer when the analysis is performed manually (either through computer-assisted classifications or manual digitizing). The combination of all these sources of delay is termed the functional latency of the NRT monitoring system.

In addition to spatial resolution, functional latency is one of the technical factors that will determine the effectiveness of the system. As mentioned, there is a trade-off between spatial resolution and temporal resolution: the higher the spatial resolution, the lower the temporal resolution; the lower the temporal resolution, the larger the gaps between repeat data acquisitions; the larger the gaps, the greater the functional latency and the less effective the system will be for rapid response. Functional latency is particularly important when tracking forest degradation as the spectral signal can rapidly disappear due to vegetation regrowth. Nevertheless, a system can still be useful for guiding adaptive management activities even when the functional latency is high.

Precision and validation

High-resolution satellite data such as Landsat are usually pre-processed by satellite data providers to a horizontal root mean square (RMS) error of between 50-250m, and the geographic locations of forest activity detected with these data are sufficiently precise that a person using a consumer-grade GPS unit can track down and travel to the activity based on the reported locations extracted from the imagery. In contrast, the geographic locations of active fire detections produced by MODIS are determined by the center point of the $1km^2$ thermal channel pixel; the actual location of the fire detected by MODIS may be located up to 500m from the centerpoint of the pixel, thus complicating navigation to the location of the reported fire activity.

The accuracy of many NRT forest monitoring products often lack systematic validation. This is partly due to the nature of near real-time information where the primary concern is speed of data delivery. However, accuracy is a critical factor in building and sustaining user confidence in NRT products; if data accuracy becomes suspect, it can permanently damage the reputation of the provider institution and, more broadly, undermine people's willingness to use NRT data as a source of information for decision making. In certain cases, national governments have refused to use data from NRT forest monitoring systems that have not been officially vetted or designated as a data provider.

Given the worldwide prevalence of GPS-enabled mobile smart phone technology and data sharing through blogs and social networks, there is now ample opportunity for users to collect field observations (e.g., GPS-tagged photos) and provide feedback for validation of NRT forest monitoring data. Some of the existing NRT monitoring systems are now being configured to capture this information via smart phone applications and blogs. Developing privacy safeguards and field data verification controls are a critical part of this process, both to guarantee the safety of individuals submitting information on destructive forest activity, and to ensure that field data are accurate.

7.3.5 Examples of existing near real-time forest monitoring systems

NRT monitoring with earth observation satellite data can help overcome many challenges associated with reducing illegal or undesirable forest activities and their impacts, and strengthening activities aimed at prevention, preparedness, and response to deforestation, encroachment and fire related to REDD+. NRT monitoring plays a critical role in alerting park administrators, field-based forest managers, patrols, local non-governmental organizations (NGOs) and local communities of wildfire activity, and enhances the ability of national and sub-national governments to respond to threats in a strategic manner. Fire risk forecasts are important in facilitating advanced preparation aimed at averting, reducing and managing deforestation related to out-of-control wildfire. Monitoring fire incidence and fire risk provides critical summary and trend data to help inform policy, planning and land management decisions.

Conservation International's Fire Alert / Fire Risk / Deforestation and Encroachment Alert Systems

A partnership between Conservation International (CI), the University of Maryland (UMD) and host-country institutions has enabled the development of a suite of NRT fire and deforestation monitoring and forecasting applications that channel satellite observations directly to international users responsible for decision-making activities and actions related to wildfires. These applications include: the Fire Alert System (FAS)

(http://firealerts.conservation.org), the Fire Risk System, and the Deforestation and Encroachment Alert System. FAS is an automated and customizable alert delivery system based on MODIS active fire data that provides subscribers with a range of products tailored to their needs (Figures 7.1, 7.2). The Fire Risk System is an automated daily risk model that estimates moisture fluctuations in litter fuels on the forest floor with daily inputs from MODIS and other weather satellites (http://firerisk.conservation.org) (Figure 7.3). The Deforestation and Encroachment Alert System is a near real- time alert system founded on rapid analysis of Landsat and ASTER imagery.

Figure 7.2: A subscription and user management page for a fire-alert system

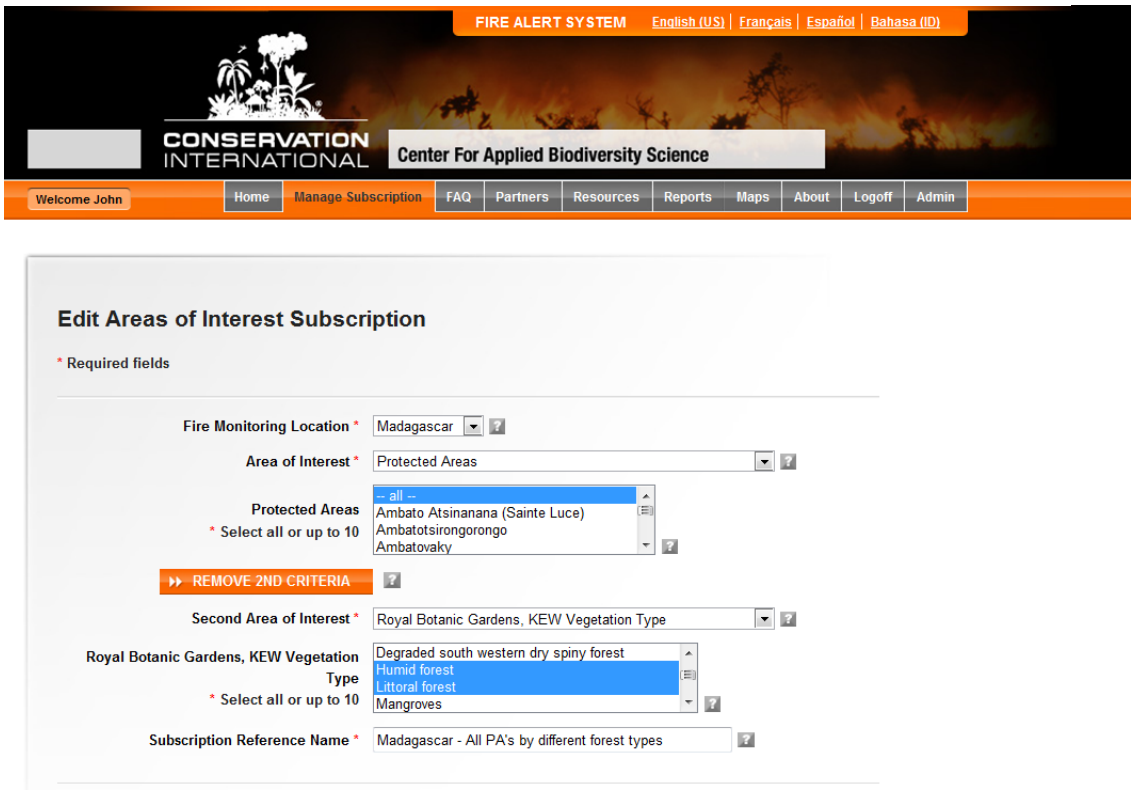
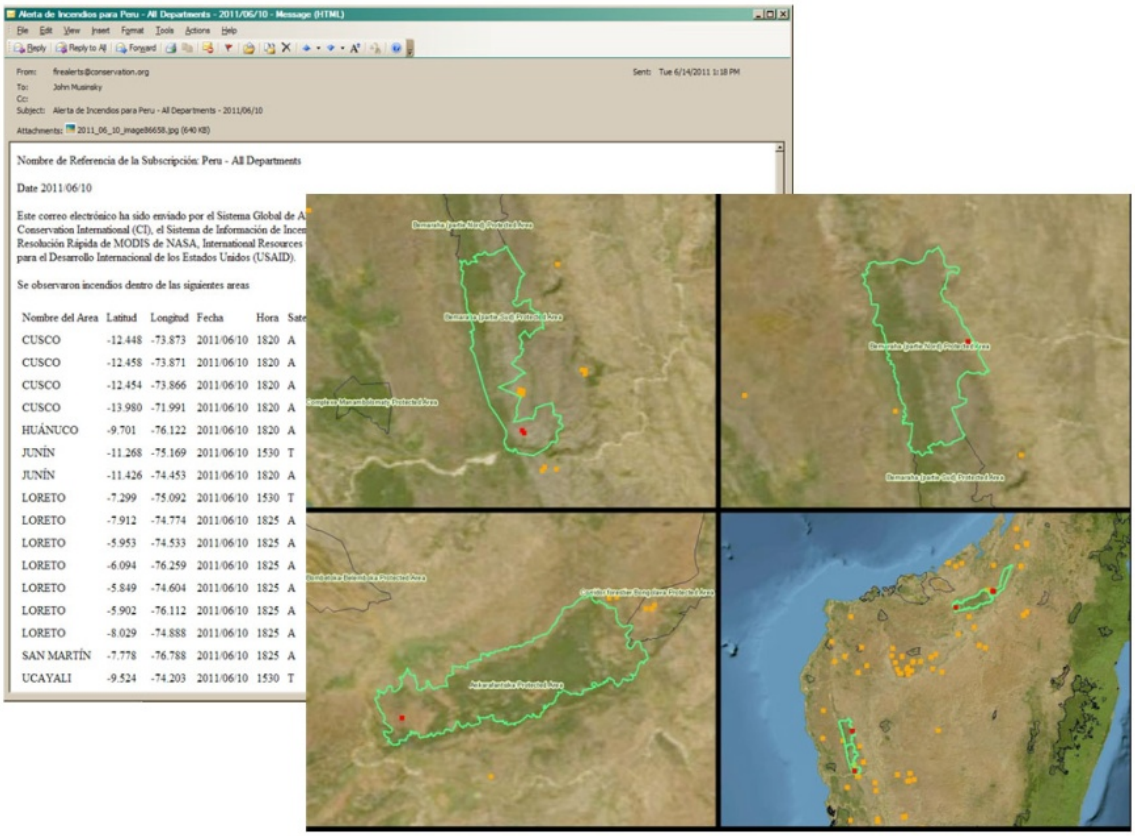


Figure 7.3: Sample email alert and JPEG attachment notifying fire activity in a user-specified area of interest



With more than 1,300 subscribers from 45 countries, users of these monitoring systems have found critical applications for these data in forest law enforcement, protected areas management, REDD+ forest carbon projects, community education, and policy development related to conservation and sustainable development, among others (NASA, 2010).

Initial development began in 2002 when CI created the first near real-time email alert system on record, a manual prototype that delivered simple email alerts using MODIS active fire observations from the UMD Web Fire Mapper overlaid on all protected areas in Brazil, Bolivia, Madagascar, Namibia, Paraguay, South Africa and Tanzania. In September 2007, with support from the United States Agency for International Development (USAID), CI developed and launched an automated version of the Fire Alert System (FAS) for Madagascar to channel real-time data generated by MODIS RapidFire to field personnel and government agencies responsible for natural areas management, fire suppression, and forest conversion. Version 1.0 of the automated FAS produced daily and weekly alerts tailored to different users' needs, running queries on land cover, vegetation types, Key Biodiversity Areas, protected areas and administrative units.

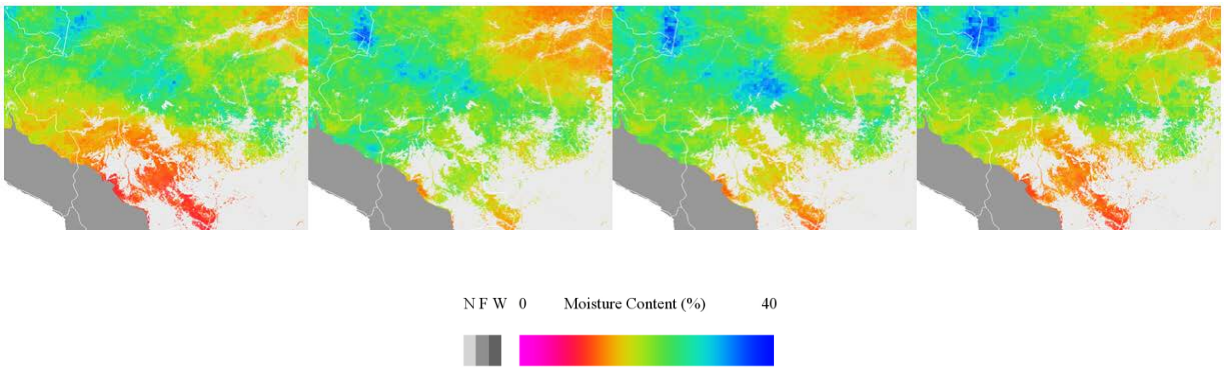
Version 2.0 of the FAS expanded the geographic coverage of the automated system to include Bolivia, Peru and the islands of Sumatra and Kalimantan in Indonesia. It also added public access to the suspected illegal activity alerts generated for parks in Indonesia and included email attachments with custom images, text files, GIS Shapefiles and GoogleEarth KML files of fires occurring within user-defined areas of interest, as well as on-line reports and maps.

The Fire Risk System is an application using satellite bioclimatology to model forest flammability. The model is based on the relationship between moisture content and flammability of fuels on the forest floor (i.e., litter and woody debris). Fuel moisture content fluctuates with rainfall events and weather conditions, causing moisture exchange with the surrounding air. The model assumes that fuel is ignitable at moisture contents of 20 percent or less, based decades of field experiments by the US Forest Service quantitatively describing the relationship of fuel moisture and flammability risk. The Fire Risk System uses NRT satellite estimates as inputs to the US Forest Service Fire Danger Rating System equations for estimating the moisture content of

fuels. It generates daily maps of forest flammability at 5km resolution based on the previous day's fuel moisture content and the current day's air climate conditions (Figure 7.3).

The satellite observations used in this model are rainfall duration from TRMM 3B42RT and near-surface temperature and relative humidity from MODIS MOD07L2 Atmospheric Profiles. The model runs nightly and pulls MODIS and TRMM data from their ftp data pools to generate maps of fire risk, daily rainfall sum, days since last rainfall, and the commonly used Keetch-Byram Drought Index. The model is currently used by *Fundación Amigos de la Naturaleza* in Bolivia and the Bolivian forestry department for district and community level communications.

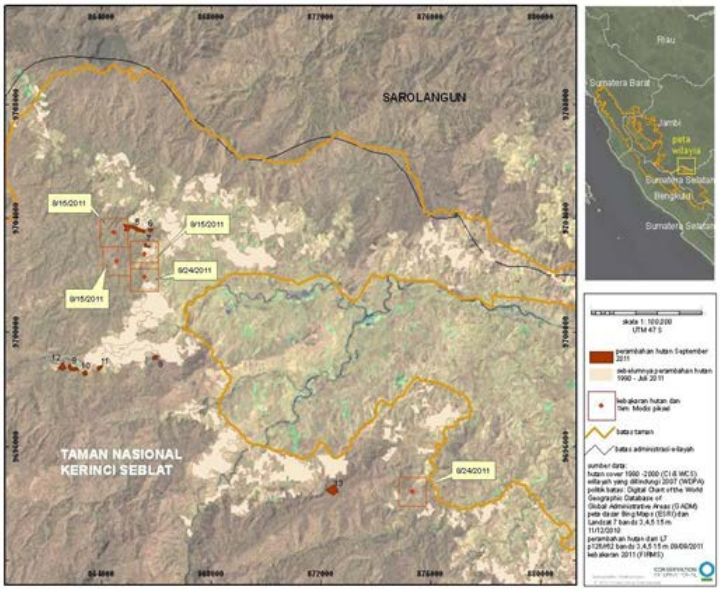
Figure 7.4: Example of forest flammability model outputs used in an alert system. Displayed are the spatial patterns of daily moisture content for coarse fuels, a useful indicator of fire risk. Data are for October 12th-15th, 2003 chronologically from left to right. Areas from yellow to red indicate moisture values of 20 percent and less, indicating increasing flammability for that fuel class. Light grey is non- forest (N), medium grey is forest above 500m above sea level (F), and dark grey areas are water (W). From Steininger et al (2013), http://firerisk.conservation.org.



The Deforestation and Encroachment Alert System uses the same approach as the FAS: NRT delivery of observations of illegal forest activity to a range of in-country stakeholders who can utilize the information for rapid response. Landsat and ASTER satellite archives are continually surveyed and, as soon as new data are available, the images are downloaded and analyzed for evidence of encroachment occurring within 2.8 million hectares of protected areas and REDD+ sites in Indonesia and Madagascar. The deforestation and encroachment alerts (Figure 7.4) complement the fire alerts. While the high-resolution of Landsat and ASTER are characterized by much greater latency than MODIS imagery, they allow for delineation of deforested areas where fire activity may have been detected by MODIS. Reports from counterparts in the field reiterate that the combination of both fire alert and encroachment alert systems has catalyzed and focused numerous enforcement campaigns leading to interdiction and deterrence of illegal forest activity within national parks.

Figure 7.5: Deforestation and encroachment alert for Kerinci Seblat National Park, Indonesia

ID	Citra Satelit Baru Tanggal	Dasar Tahun	X_UTM	Y_UTM	* Pelanggaran Batas Wilayah (ha)	Ketinggian (m)	Lereng (deg)	Jarak Dari Sungai (m)	Jarak Dari Batas Taman (m)	Jarak Dari Jalan (Km)	Jarak Dari Desa (km)	Desa	Kabupaten	Provinsi
0	September 2011	Juni 2011	724964	9789571	1.6	309	3	143	1604	8	15	Airhadji	Pesisir Selatan	Sumatera Barat
1	September 2011	Februari 2011	813023	9706797	5.2	1400	3	760	2291	2	27	Beringintingi	Merangin	Jambi
2	September 2011	Februari 2011	812720	9706893	0.5	1405	8	608	2549	2	28	Beringintingi	Merangin	Jambi
3	September 2011	Februari 2011	812794	9706587	0.4	1366	10	450	2580	3	28	Beringintingi	Merangin	Jambi
4	September 2011	Februari 2011	812522	9706857	1.6	1403								
5	September 2011	Desember 2010	865152	9703657	10.1	260								
6	September 2011	Desember 2010	865778	9703605	1.5	250								
7	September 2011	Desember 2010	865635	9703048	1.6	242								
8	September 2011	Juli 2011	865954	9699114	2.1	325								
9	September 2011	Desember 2010	862928	9698746	4.4	269								
10	September 2011	Desember 2010	863384	9698573	2.3	301								
11	September 2011	Desember 2010	863927	9698768	2.2	296								
12	September 2011	Desember 2010	862563	9698791	4.6	294								
13	September 2011	April 2011	872436	9694452	8.4	562								
14	September 2011	April 2011	774853	9802448	1.7	1391								
15	September 2011	Desember 2010	767465	9803026	2.2	1819								
16	September 2011	Desember 2010	765592	9802287	0.8	1798								
17	September 2011	Desember 2010	765978	9800246	1.2	1712								
18	September 2011	Desember 2010	765647	9800088	2.1	1684								
19	September 2011	April 2011	776923	9797593	2.5	1302								
20	September 2011	Agustus 2011	776978	9797418	0.2	1285								
21	September 2011	Agustus 2011	777020	9795880	1.8	1258								
22	September 2011	Desember 2010	777749	9792280	0.8	1148								
23	September 2011	Agustus 2011	778938	9791645	9.4	1228								
24	September 2011	Agustus 2011	778250	9792204	3.3	1241								



A new, "integrated forest and fire monitoring and forecasting system for improved forest management in the tropics" based on these existing systems, called FIRECAST, is now under collaborative development by CI, NASA Ames Research Center and NASA Goddard Space Flight Center, with support from a NASA Wildland Fires grant. FIRECAST will deliver automated NRT email and text messaging alerts for active fires, daily/weekly/seasonal fire risk forecasts, and MODIS-based deforestation probabilities occurring within user-defined areas of interest, and offer an online space for data sharing and collaboration among users.

Fire Information for Resource Management System (FIRMS)

The Fire Information for Resource Management System (FIRMS) is the most important and influential NRT fire monitoring system created to date. Developed by UMD in conjunction with NASA's Goddard Space Flight Center, FIRMS is now located at NASA EOSDIS (Earth Observing System Data and Information System) (http://earthdata.nasa.gov/data/nrt-data/firms). FIRMS has four components: Web Fire Mapper, an interactive web-based mapping system created in 2001; email alerts for protected areas (originally developed in collaboration with CI); a data downloading tool that enables users to download MODIS active fire data

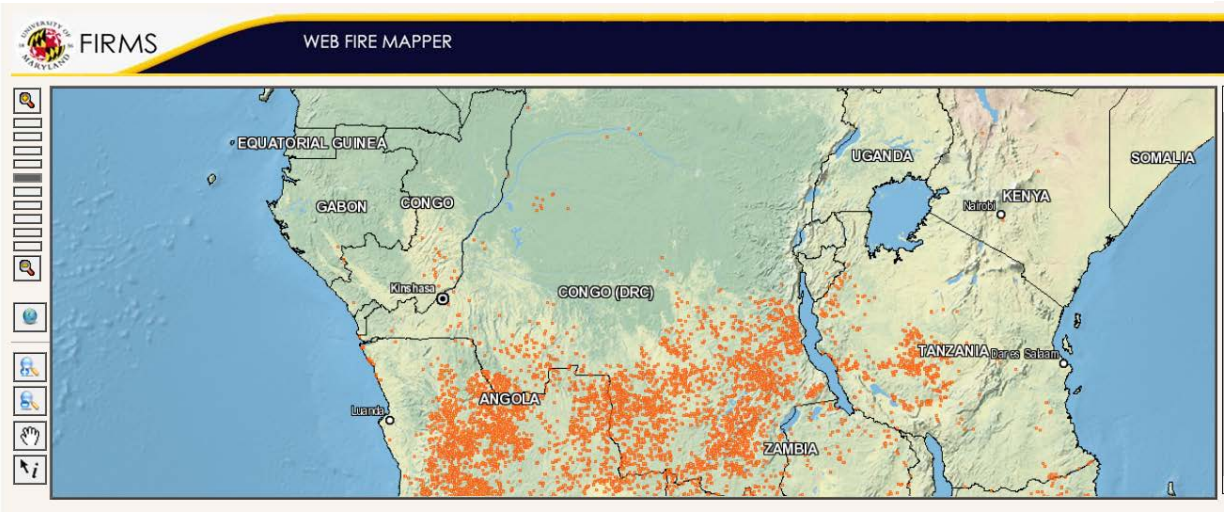
Figure 7.6: FIRMS Components

based on date ranges; and access to daily MODIS image subsets (Figures 7.5, 7.6) (Justice et al, 2011; Davies et al, 2009). The open source Web Fire Mapper application allows users to view and query active fire data for any specified date range, and view MODIS burned area images for the entire globe, one month at a time. FIRMS processes the NASA MODIS Level 3 Monthly Tiled 500m Burned Area Product (MOD45A1 http://modis-fire.umd.edu) and makes it available in images displayed at resolutions of 8 km, 4 km, or 2 km. The user interface was designed using the Google Web Toolkit (GWT) application programming interface, a Java-based software development framework used to develop AJAX applications. The core WebGIS functionality is provided through Minnesota MapServer (http://mapserver.gis.umn.edu) via a common gateway interface. For the spatial database, PostgreSQL (http://www.postgresql.org) relational database was used in combination with the PostGIS spatial database extension (http://postgis.refractions.net).

The email alerts messaging component of FIRMS delivers MODIS active fire information for specified protected areas or defined areas of interest, and allows users to choose NRT alerts daily, or weekly summaries. Users can select any area for notification by selecting an area on an interactive map, or selecting a specific country or protected area via drop down boxes. Users that select a protected area can also include a buffer around the protected area. The email alert system supports the option to include a map image and a Comma Separated Values (CSV) text file of fire coordinates. The map image enables users to readily visualize the exact location of the fire, and the CSV file can be ingested in to a GIS for further analyses or used to build up a local database of fires. MODIS active fire data are available through FIRMS in a range of easy-to-access data formats, including CSV text files, ESRI Shapefiles, KML files, NASA World Wind files and Web Map Service (WMS) files. Providing active fire information in vector format, such as an ESRI Shapefile, has the advantage of small file sizes and provides the option of querying attribute information.

MOD14 active global fire detections are supplied by NASA LANCE. These products are produced in NRT, within 3 hours of observation. For science applications, users are also given the option of accessing collection 5 data processed by FIRMS using Level 2 data from the DAAC.

Figure 7.7: FIRMS Web Fire Mapper



Global Fire Information Management System (GFIMS)

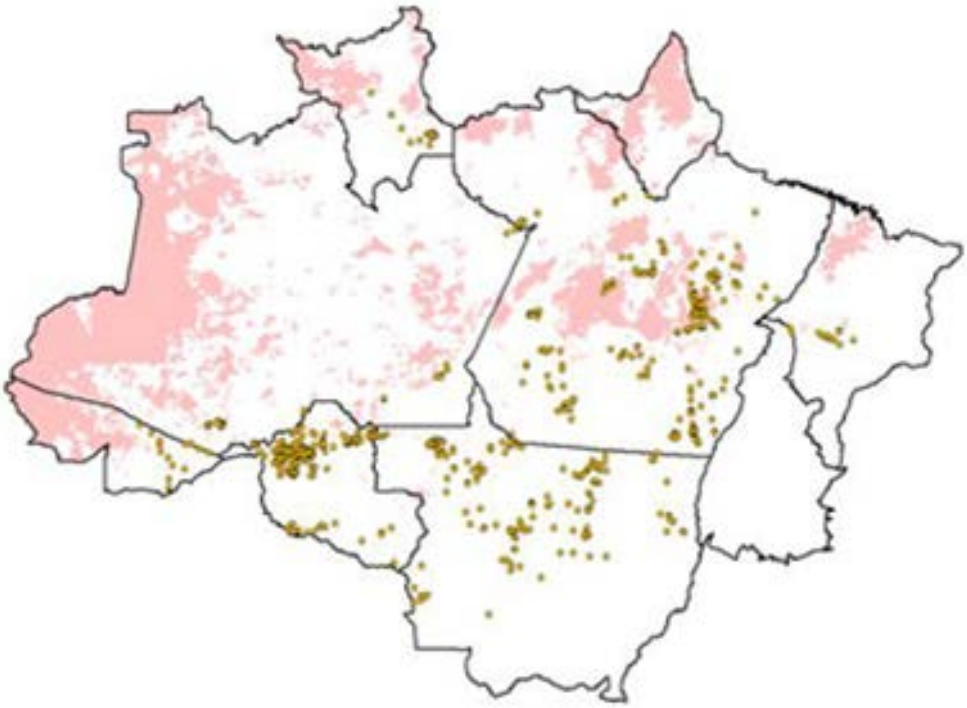
The Global Fire Information Management System (GFIMS) integrates remote sensing and GIS technologies to deliver MODIS hotspot/fire locations and burned area information to natural resource managers and other stakeholders around the world. GFIMS is hosted at the Department of Natural Resources (NRD) of the Food and Agriculture Organization (FAO) of the United Nations and is based on FIRMS. GFIMS complements existing NRT information systems that deliver data and services to ongoing monitoring and emergency projects in FAO headquarters and field offices, in other United Nations organizations, and the

general public. The Fire Email Alerts is the GFIMS open source email alert service that notifies registered users of MODIS-derived active fires in a specified area of interest, and delivers an email alert directly to the users by reading a database of user-entered subscription information (user profiles). The user subscription information includes their area of interest, alert frequency, and email delivery preferences. The email alert includes a summary of the number of fires detected and an attached tabular list of fires with their attributes in CSV format. Daily and weekly fire alerts are sent from the GFIMS system, whereas near real-time alerts are sent directly from the MODIS Rapid Response (MRR) facility to avoid potential delays caused by relaying the data from the MRR to the GFIMS servers.

DETER and PROARCO

The DETER system, operated by the Brazilian Space Research Agency (INPE) produces monthly/bi-monthly Amazon deforestation alerts to facilitate effective control of forest clearing (Figure 7.7). DETER alerts are sent to the Brazilian Institute for Environment and Natural Resources and state government agencies responsible for responding enforcing forest legislation.

Figure 7.8: Yellow dots represent the location of deforestation in an alert issued by DETER



DETER uses MODIS data, from which deforestation events with an area larger than 25 hectares can be detected. While some deforested areas are not identified by the system due to cloud cover, the low spatial resolution used by DETER is compensated for by daily observations that are mosaicked into monthly wall-to-wall assessments of the entire legal Amazon.

DETER provides an important source of data for control and enforcement as the high temporal resolution but coarse spatial resolution data are complemented by annual monitoring of forest removal using INPE's PRODES (www.obt.inpe.br/prodes). The PRODES system uses high resolution Landsat and CBERS imagery capable of showing small-scale deforestation. A complement to DETER and PRODES is INPE's PROARCO fire monitoring system (http://www.dpi.inpe.br/proarco/bdqueimadas/), a web-based mapping tool publishing daily active fire detections from MODIS, AVHRR and GOES.

IMAZON Deforestation Alert System (SAD)

The Deforestation Alert System *(Sistema de Alertas de Desmatamento*-SAD) is a satellite-based monitoring system operated by the Amazon Institute of People and the Environment (IMAZON), a national NGO based in Belém, Brazil. SAD produces a monthly bulletin of deforestation and degradation for the legal Amazon that can be downloaded from the IMAZON web page or circulated to subscribers in the form of email or mobile phone alerts. SAD data are also available through ImazonGeo (Figure 7.8), an interactive web portal for distributing spatial information on the status and threats to forests and protected areas in the Brazilian Amazon. The IMAZON SAD team creates a temporal mosaic of daily MODIS MOD09GQ and MOD09GA products, filters clouds, computes a resolution merge between the 500m multispectral and 250m visible bands, and produces a Normalized Difference Fraction Index image showing the relative abundance of green vegetation, soils, shade and non-photosynthetic vegetation components that are used in time-series to detect deforestation and degradation over time. SAD has been operating in the State of Mato Grosso since August 2006 and in the Amazon since April 2008, and is often used as a source of independent, corroborative measurement of Amazon deforestation statistics produced by INPE's PRODES program.

Figure 7.9: ImazonGeo

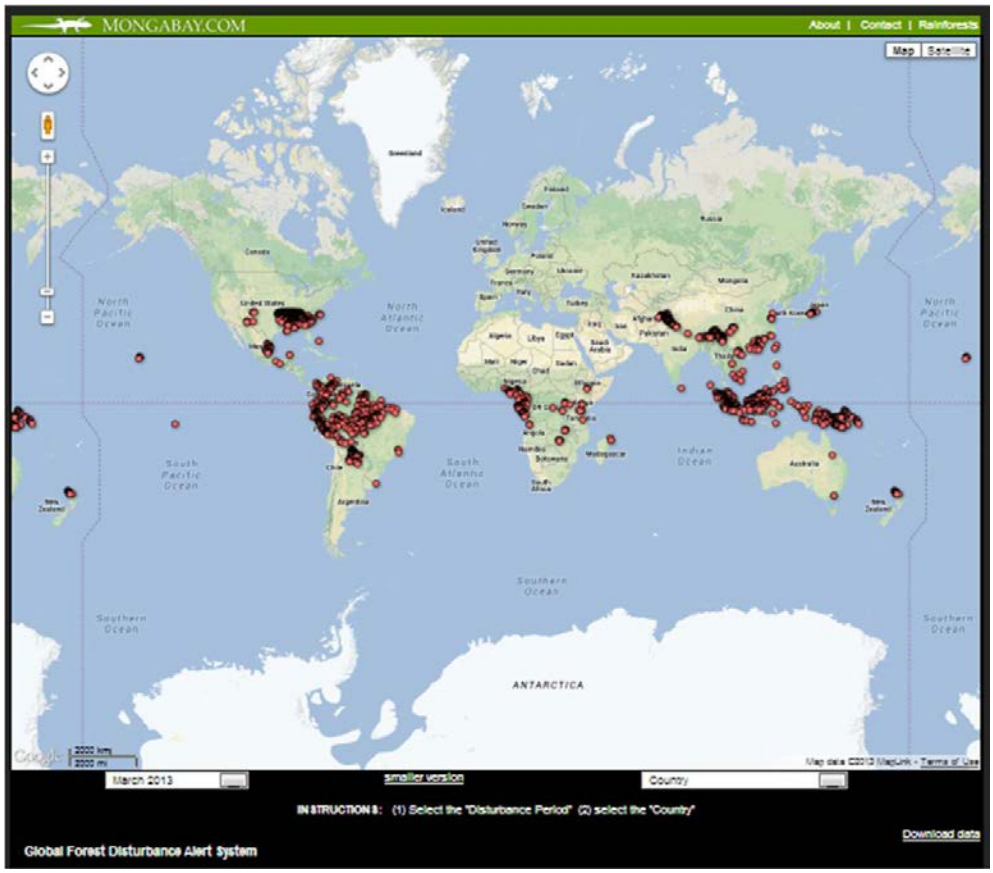
QUICC MODIS deforestation products and the Global Forest Disturbance Alert System (GloF-DAS)

Investigators at NASA Ames Research Center and California State University have developed a custom 5km resolution MODIS satellite product called the "Quarterly Indicator of Cover Change" (QUICC) for all

forested areas of the globe. The global QUICC change product is based on a quarterly time-series comparison of MODIS daily vegetation index images at the same time each year (March, June, September and December) for all forest and woodland areas that have lost at least 40% of their green vegetation cover during the previous year.

The QUICC products are distributed through the GloF-DAS web portal (http://rainforests.mongabay.com/deforestation-tracker/) hosted by Mongabay.com, as well as other third-party data distribution systems (Figure 7.9). GloF-DAS is based on the NASA QUICC product and provides data on forest disturbance globally to map all large-scale forest cover change (including fire impacts) on a quarterly basis. The team updates and distributes its global QUICC products to GloF-DAS as soon as the newest quarterly MODIS worldwide vegetation index image is available.

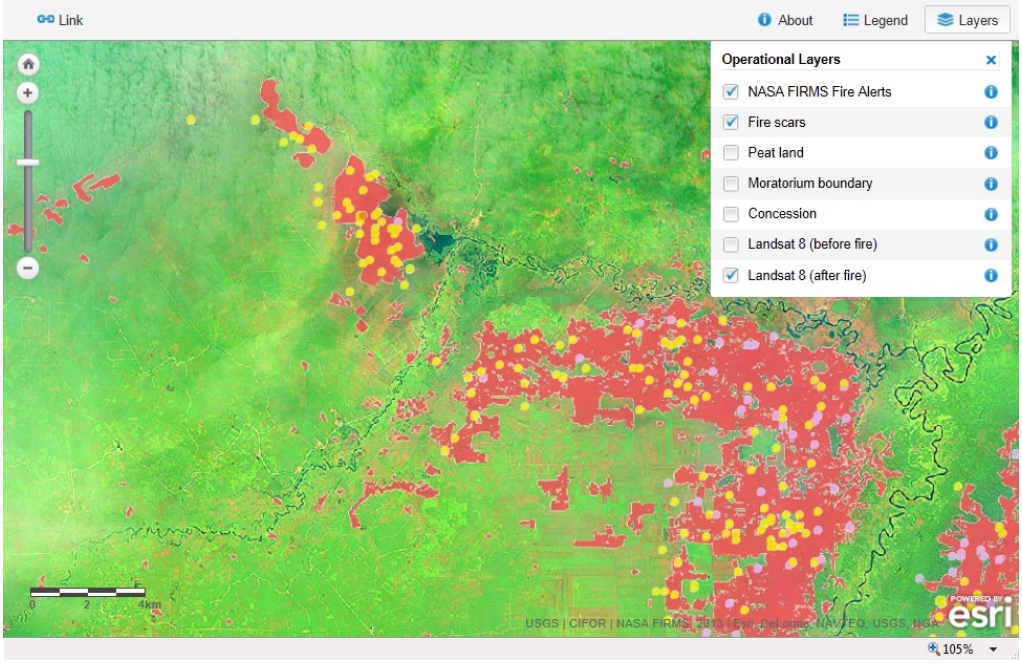
Figure 7.10: GloF-DAS



CIFOR Interactive Fire Risk Tool

The Center for International Forest Research (CIFOR) has created a web-based fire risk mapping application (http://www.cifor.org/map/fire/) that allows users to overlay NRT satellite data on active fire locations from FIRMS and fire scars mapped by CIFOR from the most recent Landsat 8 imagery on peatlands, logging moratorium boundaries, timber and oil palm plantation concessions, and raw Landsat 8 images (before and after burns) (Figure 7.10).

Figure 7.11: CIFOR Interactive Fire Risk Tool



7.3.6 Utility of near real-time monitoring systems

CI conducted a subscriber survey in November 2011 to collect feedback on the utility of fire and forest monitoring systems in developing country contexts. 28 percent of the 118 respondents represented national NGOs, 22 percent represented international NGOs, 20 percent were associated with government agencies, 20 percent with academic institutions and the press, and 10 percent with the private sector. Over 21 percent of the respondents were using the fire alerts data to support forest surveillance and monitoring efforts; 19 percent for protected areas management; 17 percent to assist with policy development related to conservation and sustainable development; 13 percent for research; 12 percent for education and training; and 3 percent for social and public health-related activities. Further, the fire data were perceived as having high intrinsic value, with 73 percent of respondents reporting that the fire alerts were very useful for their work or research. Respondents also indicated that NRT and seasonal fire risk forecasting information presented valuable contributions to their decision-making activities. The survey results also confirmed numerous anecdotal reports from users in Madagascar, Indonesia, Peru and Bolivia about how forest and fire monitoring data facilitate conservation and management objectives, including helping to inform strategy, triggering official enforcement responses to deforestation and degradation, helping to build awareness, enabling fire control and prevention, etc. Further, in Madagascar a series of meetings conducted as part of a mid-term project evaluation for USAID revealed that fire monitoring data were being used for a broad range of applications including active fire suppression, fire control and prevention workshops, prioritizing resource management based on fire intensity and ecological vulnerability, improving protected areas and plantation forest management, and studying the influence of climate change on fire frequency.

7.3.7 Conclusion

To-date, multiple NRT systems have been generated and continue to be improved. As more satellite data options become available, and associated acquisitions become less costly, greater opportunities for NRT systems that can be incorporated into alert systems exist. Further, NRT systems represent a useful component to any MRV system. While such systems may not contribute directly to the required reporting, they provide a robust first look and increase the potential for countries and programs to improve adaptive management and enforcement capacities.

7.3.8 References

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