Measuring and Monitoring Terrestrial Carbon

The State of the Science and Implications for Policy Makers

August 2009

Prepared by Tanja Havemann for

The Terrestrial Carbon Group

www.terrestrialcarbon.org

THE HEINZ CENTER

and

UN-REDD PROGRAMME

The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries

www.un-redd.org

PARTICIPANTS

UN-REDD

Launched in 2008, the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD) is a joint effort between the UN Environment Programme (UNEP), the UN Development Programme (UNDP) and the Food and Agriculture Organisation (FAO). The aim of this initiative is to contribute to the development of capacity for implementing REDD and to support the international dialogue for the inclusion of a REDD mechanism in a post-2012 climate regime.[1]

FAO

Founded in 1945, FAO helps countries to improve agriculture, forestry and fisheries practices and ensure good nutrition for all, while providing a neutral forum for the discussion and negotiation of policy and also acts as a source of information and knowledge.[2] FAO is the lead organisation for monitoring and reporting aspects of the UN-REDD programme, based on its global forest assessment activities.

The Terrestrial Carbon Group project at the Heinz Center

The Terrestrial Carbon Group is an international group of recognized specialists from science, economics and public policy, working together to catalyze the inclusion of terrestrial carbon in the international response to climate change.[3] A major objective is to create an effective, viable approach for carbon accounting that could be used for the broader inclusion of terrestrial carbon, including REDD, in the UNFCCC. The Terrestrial Carbon Group project is housed as the H. John Heinz III Center for Science, Economics and the Environment, a non-profit, nonpartisan organisation dedicated to improving the scientific and economic foundation for environmental policy.[4]

Acknowledgements

This report would not have been possible without the valuable contribution of the Contact Group and the Reference Group. The Contact Group represents an international and technically diverse group of organisations, with key roles to play in the shaping of a future UN agreement on REDD. The Contact Group helped to shape this report, and also reviewed and provided comments on the document in its entirety. The Reference Group are a group of individuals, who contributed specialised technical expertise related to the subject of measuring biomass and other terrestrial carbon pools to this report, or who reviewed and commented on Chapters 3 and 4 of this report. The report was compiled and written by Tanja Havemann, under the guidance of Christine Negra of the H. John Heinz III Center for Science, Economics and the Environment.

[1] www.un-redd.net

[2] www.fao.org

[3] http://www.terrestrialcarbon.org/index.html

[4] http://www.heinzctr.org/

We thank the following for their invaluable comments, insights and feedback:

Ken Andrasko (Senior Policy Analyst, Carbon Finance Unit, World Bank), **Mario Boccucci** & **Niklas Hagelberg** (Senior Programme Officer, Forests and Climate Change & Programme Officer, Freshwater and Terrestrial Ecosystems Branch of UNEP), **Tim Clairs** (Senior Technical Advisor (REDD), Environment and Energy Group, UNDP), **Paul Drichi** (Director, Plantations Divsion, National Forest Authority of Uganda), **Peter Holmgren** (Director, Environment, Climate Change and Bioenergy, FAO), **Christoph Kleinn & Lutz Fehrma** (Center for Tropical and Subtropical Agriculture and Forestry, University of Göttingen), **Werner Kurz & Stephen Kull** (Senior Research Scientist, Global Change and Landscaope Ecology & Accounting Liaison Officer, Natural Resources Canada, Canadian Forest Service), **Carmen Meneses** (CONAFOR, Mexico), **Dennis Ojima** (Senior Scholar and Co-Director of Mitigation Programs and Senior Research Scientist at Natrual Resources Ecology Laboratory, the H. John Heinz III Center for Science, Economics and the Environment and Colorado State University), **Devendra Pandey** (Director, Forest Service of India), **Greg Reams** (FIA National Program Leader, USDA Forest Service), **Tomas Thuresson** (Director, Harad Skog), **Andreas Tveeteras** (Senior Advisor, The Government of Norway's International Climate and Forest Initiative, Norwegian Ministry of the Environment)

We also thank the following for their insights and references, particularly regarding some of the more technical issues:

Greg Asner (Stanford University), **Richard Conant** (Colorado State University), **Eric Davidson** (Woods Hole Research Center), **Owen Evelyn** (Forestry Department of Jamaica), **Jacqueline Gehrig-Fasel** (TREES Consulting, Perspectives), **Holly Gibbs** (University of Wisconsin), **Kailash Govil** (Consultant to FAO), **Matt Hansen** (South Dakota State University), **Alfred Hartemink** (University of Wageningen), **Jyrki Jauhiainen** (University of Helsinki), **Johannes Lehmann** (Cornell University), **Olga Krankina** (Oregon State University), **Danilo Mollicone** (FAO), **Yadvinder Mahli** (Oxford University), **Pete Manning** (Imperial College London), **Chad Oliver** (Yale University), **Phil Polglase** (CSIRO, Australia), **N.H. Ravindranath** (Indian Institute of Science), **Neil Sampson** (The Sampson Group), **Alberto Sandoval** (FAO), **David Shoch** (TerraCarbon), **Pete Smith** (University of Aberdeen), **Carla Ramirez Zea** (FAO), **Greg Reams** (USDA), **Steve Running** (University of Montana), **Robert Waterworth** (Department of Climate Change, Australia)

ACRONYMS

Acronym	Definition
AAU	Assigned Amount Unit
A/R	Afforestation/Reforestation
ABG	Above ground (biomass)
AFOLU	Agriculture, Forestry and Other Land Use
BEF	Biomass Expansion Factor
BGB	Below ground (biomass)
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CO_2	Carbon Dioxide
COP	Conference of the Parties
DBH	Diameter at Breast Height
EFDB	Emissions Factor Data Base
EPA	Environmental Protection Agency (US)
LDC	Least Developed Country
GHG	Greenhouse Gas(es)
GIS	Global Information System
H or h	Height
HWP	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
lCER	Long-term Certified Emission Reduction
MAI	Mean Annual Increment
MOP	Meeting of the Parties
MRV	Monitoring, Reporting, Verification
NFI	National Forest Inventory
POA	Programme of Activities
RED	Reducing Emissions from Deforestation
REDD	Reducing Emissions from Deforestation and Degradation
REL	Reference Emission Level
RMU	Removal Unit
RS	Remote Sensing
SOM	Soil Organic Matter
tCER	Temporary Certified Emission Reduction
UNFCC	United Nations Framework agreement on Climate Change

CONTENTS

This Page is Intentionally Blank

EXECUTIVE SUMMARY

Improved management of the carbon stored in the world's terrestrial vegetation and soil is a necessary part of the global effort to avoid dangerous climate change. Emissions from terrestrial carbon currently represent roughly one-third of all greenhouse gas emissions annually. And terrestrial carbon management represents roughly half the cost-effective mitigation available globally up to 2030.[5] Terrestrial carbon management also has critical links to economic development, food security, and climate change adaptation. However, to date, the international response to climate change has not provided significant incentives to formal and informal land managers in developing countries to manage terrestrial carbon for climate change outcomes. Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are expected to agree in December 2009 to a new set of incentives that would apply to some range of terrestrial carbon, possibly starting with forests (avoided emissions and new sequestration) and moving over time to include the whole agriculture, forestry and other land use (AFOLU) continuum, as described by the Intergovernmental Panel on Climate Change (IPCC).

Regardless of the exact outcome in Copenhagen, any incentive system will rely heavily on the ability to measure terrestrial carbon stocks and monitor changes to the carbon stocks and / or carbon fluxes over time.

This report is intended as a short and policy-neutral introduction to, and summary of, methods to measure and monitor terrestrial carbon, with a focus on the above-ground biomass pool. The report provides an overview of the policy landscape, in terms of existing UNFCCC and Kyoto Protocol requirements and the widely accepted guidance issued by the IPCC. It also provides an overview of existing terrestrial carbon information sources, and initial steps to be taken prior to measurement and monitoring activities (land cover classification and sampling). This is followed by short technical descriptions of the different categories of methods available for measuring and monitoring terrestrial carbon, i.e. field measurements, remote sensing and models. These methods are evaluated in the context of possible system designs for further including targets and incentives for sustainable land management under the Kyoto Protocol.

Total terrestrial carbon stock at a point in time is a function of the carbon density and the areal extent of each land use class in an area of interest. Changes in stock result from changes to the carbon density of each land use class, and from changes in the area of different types of land use classes. Measuring the carbon density under certain types of land uses, as well as monitoring if and how the density, area and distribution of land use classes change, is therefore a necessity. Currently, field measurement methods are the only reliable tool for obtaining carbon density estimates. In order to extrapolate and convert field measurements into estimates of carbon stock, however, conversion equations are required. These are themselves based on field measurements. Data on the distribution of land use classes can be obtained by field methods, but it is usually more efficient to use remote sensing approaches. Remote sensing can also be efficiently used to track changes to the

[5] Pathways to a Low Carbon Economy: Version 2 of the Greenhouse Gas Abatement Cost Curve, McKinsey & Company 2009.

relative distribution of land use classes over time. Models combine field measurements and remote sensing data in ways that make it easier to estimate carbon stock changes over time, and to predict future changes.

Most, if not all, of these methods have already been used alone, or in combination to measure carbon or biomass stocks and / or changes. For example, they may already be used for commercial activities, to meet existing national policy objectives, and to carry out carbon project activities under the Kyoto Protocol or for the voluntary market. The methods described in this report are rapidly becoming more widespread and advanced; the pace of development could be increased given more significant and clearer incentives in the second commitment period of the Kyoto Protocol, or a similar agreement. Although the policy framework into which these methods would fit is currently unclear, most of the blockages to further incentivising better management of terrestrial carbon (especially forest carbon), are political in nature rather than technical.

A variety of proven measurement methods exist, but there is variability in terms of:

- The carbon pools that can be measured, i.e. above-ground, below-ground, soil organic matter, litter, dead wood and harvested wood products;
- Measurement scale (fine, medium, coarse);
- Maturity of the method;
- Initial and on-going costs;
- Capacity requirements, e.g. equipment and technical know-how; and
- Frequency with which methods can be applied – i.e. suitability for initial stock measurement, and for periodic measurement, or monitoring.

In the near term, most countries would be able to implement some form of national measurement and monitoring system for new and existing forests – particularly if the country already has relevant existing data. This is because the field methods, remote sensing methods, and models for above-ground woody biomass are generally the most mature, compared to methods for the below-ground biomass, soil organic matter, dead wood, litter and harvested wood products pools. There is, however considerable variety in the capacity to measure and monitor all types of terrestrial carbon, even within developed countries, and this is likely to persist without greater investment, technology transfer and information sharing. Improved coordination and sharing of methods would support developing countries in particular to adopt better management of terrestrial carbon at the national level. The national capacity of non-Annex I countries to measure and monitor terrestrial carbon (especially deforestation and degradation), is already being encouraged and developed with assistance from Annex I countries, multilateral agencies and a variety of other institutions.

Incentives are required to facilitate deployment of additional resources to develop quality measurement and monitoring systems. To be effective, an incentive scheme would be flexible and dynamic, and result in terrestrial carbon information that is comparable and yield results that are spatially and temporally consistent. Specifically, this could be expedited by:

- Agreeing to a set of international, practicable “best practices”, which build on IPCC guidance, and facilitate the development of more standardised measurement and monitoring methods. These would be dynamic and assessed and updated by a centralised body. Clear support would be needed for the implementation of these practices.

- Increasing the clarity and consistency of international definitions related to terrestrial carbon and maps, including land cover classes and soil maps (e.g. adoption of a common standardised land cover classification system).
- Ensuring the continuity of widely used coarse and medium-resolution remote sensing data and free access to the most commonly used types of remote sensing.
- Sharing and adapting existing models, and making adaptable versions of these available and easily accessible.
- Building a common data archive of carbon studies and remotely sensing images and data and training local staff in data interpretation. This would be additional to increased information sharing and coordination of terrestrial carbon measurement and monitoring experience, including information-sharing on pilot projects (including in the voluntary market), costs and data resources.
- Investing in the expansion and sharing of credible default-value databases and databases for conversion (allometric) equations, such as the IPCC's Emissions Factor Database (EFDB).
- Examining, enabling, and incentivising the use of measurement and monitoring systems for terrestrial carbon to collect other information, e.g. related to biodiversity or socioeconomic information.

This Page is Intentionally Blank

INTRODUCTION

"*Worldwide, living vegetation stores an enormous 500 billion tonnes of carbon, more than 60 times annual anthropogenic carbon emissions to the atmosphere. The tropics and sub-tropics combined store 430 billion tonnes of carbon, while boreal and temperate eco regions store 34 billion tonnes and 33 billion tonnes respectiv*ely."[6]

"Tropical deforestation is estimated to have released of the order of 1-2 billion tonnes of carbon per year during the 1990s, roughly 15-25% of annual global greenhouse gas emissions."[7]

Improved management of the carbon stored in the world's terrestrial vegetation and soil is a necessary part of the global effort to avoid dangerous climate change. Although oceans are a larger net global store, carbon uptake by soils and plants is the largest conduit for the removal of CO_2, the most prolific greenhouse gas, from the atmosphere.[8] Existing and new terrestrial carbon pools, above and below ground, are vital carbon stores, and are therefore significant environmental assets, or if threatened, potential environmental liabilities.

Terrestrial carbon stocks are also important indicators for other development and environmental goals: changes in stocks may have direct implications on the socio-economic health of local communities as well as on biodiversity. Measurement, the quantification of terrestrial carbon stocks, and monitoring, the observation of these stocks over time, are therefore important for reasons other than just climate change mitigation. Methods to measure and monitor changes in terrestrial carbon stocks from emissions and removals are also increasingly used to inform national land-use policy and in attracting new investment in sustainable land use projects and payments for environmental goods and services, including carbon credits.

The Kyoto Protocol, under the UNFCCC, is an agreement designed to limit the release of GHGs into the atmosphere, in order to prevent catastrophic climate change. The Kyoto Protocol created financial incentives for new terrestrial carbon sequestration[9] only (although with extremely limited impact to date). Parties to the UNFCCC are expected to agree in December 2009 to a new set of incentives that would apply to some expanded range of terrestrial carbon, possibly starting with forests (avoided emissions and new sequestration) and moving over time to include the whole agriculture, forestry and other land use (AFOLU) continuum, as described by the IPCC. Appropriate

---

[6] Ruesch, Aaron, and Holly K. Gibbs. 2008. New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000. Available online from the Carbon Dioxide Information Analysis Center [http://cdiac.ornl.gov], Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[7] Ramankutty, N., Gibbs, H.K., Achard, F., DeFries, R., Foley, J.A. and Houghton, R.A. "Challenges to estimating carbon emissions from tropical deforestation." Global Change Biology. 13 (2007), 51-66.

[8] IPCC, 2001. *Climate Change 2001: The Scientific Basis.* Chapter 3: *The Carbon Cycle and Atmospheric Carbon Dioxide.* See: http://www.ipcc.ch/ipccreports/tar/wg1/index.htm

[9] NB: The terms "sequestration" and "removals" are used interchangeably in this report.

measurement and monitoring methods are required to demonstrate that real, quantifiable and comparable emission reductions and sequestrations take place.

The following questions are under discussion: *Should the new agreement incentivise only Reducing Emissions from Deforestation (RED)? Should it also include smaller scale, or less concentrated, acts of deforestation – i.e. degradation (REDD)? To what extent should other management techniques that sustain carbon be included (REDD+)? Should the agreement include agricultural and other non-forested areas, and cover all terrestrial carbon pools (AFOLU)?* The outcomes of these discussions will have implications for the design and implementation of measurement and monitoring systems.

However, given the significance of all terrestrial carbon, it is widely accepted that eventually (in the short or medium term) countries will need to measure and monitor all terrestrial carbon.[10] This is required for two separate reasons: (i) to understand global greenhouse gas emissions and sequestration and their impact on the global atmosphere; and (ii) to provide incentives to better manage terrestrial carbon. Therefore, any system designed to reduce emissions and enhance sequestration in response to the Copenhagen agreement should be flexible and forward compatible to be able to expand to cover all terrestrial carbon.

The existing Kyoto Protocol defines terrestrial carbon pools (see Appendix I). These definitions are of key importance - they set the parameters for a potential measurement and monitoring system, including cost and capacity requirements. Additionally, measurement and monitoring requirements and data needs will also vary depending on national circumstances and implementation stage, including:

- Establishing baselines and reference levels
- On-going data collection
- Reporting and verification, including the transformation of data into a consistent format that meets agreed requirements, and the verification of data.

Currently, all Annex I UNFCCC signatories are required to report anthropogenic GHG emissions by sources and removals by sinks since 1996.[11] In order to achieve the required quality and comparability, it is recommended that they follow widely-accepted IPCC guidance, some of which is summarised in this report. Additional guidance on activities to reduce emissions from existing terrestrial sources, or to enhance or create new sinks, has also been developed by governments, multilateral agencies, NGOs and scientific research organisations, complementing existing techniques used in commercial and scientific evaluations. As a result, a range of measurement and monitoring approaches exist for terrestrial carbon. These vary widely according to end use, and consequently so do the methods, scale of measurement and monitoring, and the types of lands and land uses that they focus on. The information collected is therefore not always consistent or

---

[10] Annex I countries already report emissions and sequestration from all terrestrial carbon (with some election as to the detail with which certain land uses are reported).

[11] UNFCCC website on Annex I Greenhouse Gas Inventories: http://unfccc.int/national_reports/annex_i_ghg_inventories/items/2715.php

comparable. What is clear is that a suite of methods to measure and monitor terrestrial carbon exists, particularly for those which have received most historical interest i.e. the ABG woody biomass pool), and that these can be adapted to a terrestrial carbon accounting system, despite the current political uncertainty around the framework into which they would fit.

In anticipation of an international agreement on reducing emissions from terrestrial carbon sources and enhancing sinks, this document provides an introduction to and summary of the existing and emerging methods for measuring and monitoring terrestrial carbon, with an emphasis on the measurement of the ABG biomass pools. It also provides an evaluation of the implications of different design considerations, in terms of RED, REDD, REDD+ and AFOLU. This report is intended to serve as a resource for those engaged in climate change policy-making at the international, national and non-governmental levels.

PURPOSE AND STRUCTURE

This report focuses on the following questions:

1. What are the existing and emerging measurement methods for biomass, in the context of terrestrial carbon emissions and removals?

2. What are the technical and operational dimensions of different measurement methods?

3. How do these different measurement methods relate to policy options for RED, REDD, REDD+ and AFOLU?

These questions are relevant to monitoring too, because monitoring is essentially measurement repeated at different times.

The report examines implications only for specific aspects of measurement and monitoring methods at the national and local level. It does not consider associated legal or social issues in detail or other environmental goods and services. The report focuses on the measurement of carbon in the aboveground biomass pool.

The summary contextual framework of the report is given in Figure 1 below, which describes how different methods are used in combination. In order to evaluate these methods, it is first necessary to provide some information on the policy context of this report and to summarise a number of important and widely accepted concepts (Chapter 1). Chapter 2 provides a description of the commonly used measurement methods. This includes a section on field measurement conversion equations (allometric equations) and remote sensing. It also contains a section on models. Chapter 3 evaluates these methods in the context of different policy design options. This section also examines the suitability of the methods listed in Chapter 2 to estimate terrestrial carbon stocks and changes. Chapter 4 provides a brief conclusion and recommendations.

Figure 1: Contextual framework for terrestrial carbon measurement and monitoring

MEASUREMENT	**1. Data Collection**	▪ Carbon density (typically using field methods) ▪ Areal extent of land use category to which density estimate applies (typically using information from remote sensing)
	2. Interpretation	▪ Conversion equations to convert data from field data ▪ Models to interpret remote sensing data
	Results in: Estimate of carbon volume and geographical extent	

MONITORING	**3. Data Collection**	▪ Observation of land use changes and / or ▪ Selected measurements to determine carbon density
	4. Interpretation	▪ Conversion equations to convert data from field data ▪ Models to interpret remote sensing data ▪ May use process-based or empirical models to estimate change, depending on gain-loss or stock-change method
	Results in: Estimate of changes in carbon volume and geographical extent	

1 TERRESTRIAL CARBON MEASUREMENT: POLICY AND PRACTICAL CONSIDERATIONS

This Chapter provides a short overview of existing sources of relevant information and an introduction to general measurement issues (land cover classification and sampling).

1.1 Rationale and framework

Signatories to the UNFCCC and to the Kyoto Protocol are subject to various reporting requirements that are used to determine progress towards meeting commitments. Reporting requirements for the Convention and the Protocol and for countries with and without commitments differ but it is strongly recommended that all reporting methods follow IPCC guidance.

Under the UNFCCC, all parties must develop national inventories of anthropogenic emissions by sources and removals by sinks, although exact reporting requirements differ due to the principle of common but differentiated responsibility (Article 4.1 and 12). Annex-I countries must report anthropogenic sources and removals of GHGs not covered under the Montreal Protocol in annual GHG Inventories and periodic National Communications. Non-Annex I countries are only required to submit periodic National Communications. The Bali Action Plan encourages the use of the accepted IPCC guidelines as basis for reporting GHGs emissions and removals from deforestation (Decision 2/CP.13). The GHG inventory reports are comprised of the Common Reporting Form (CRF) tables and National Inventory Report (NIR). The Report must be transparent, consistent, comparable, complete and accurate. Relevant IPCC guidance for these submissions are the Revised IPCC 1996 Guidelines[12], GPG 2000[13], IPCC "Degradation of Forest"[14] and GPG 2003[15]. The 2006 IPCC Guidelines[16] which combine the agriculture and LULUCF categories under "AFOLU" are widely accepted but have yet to be formally approved.

According to the Kyoto Protocol, Annex I countries are required to report afforestation, reforestation and deforestation since 1990 (Article 3.3). Parties can elect to report emissions and removals from any of the following other human-induced activities since 1990 (Art. 3.4): Forest Management,

[12] IPCC, 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Available from: http://www.ipcc-nggip.iges.or.jp/public/gl/invs4.html

[13] IPCC, 2000. *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html

[14] IPCC, 2003. *Definitions and Methodological Options to Inventory Emissions from Direct Human-Induced Degradation of Forests and Devegetation of Other Vegetation Types.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/degradation_contents.html

[15] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html

[16] IPCC, 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Volume 4: AFOLU. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

Cropland Management, Grassland Management and Re-vegetation[17]. The country must provide detailed information on obligatory and elected categories in initial and annual reports (for the period 2008-2012). For activities elected under Article 3.4, a country can choose reporting frequency (annual or at the end of each commitment period). Annual reports submitted under the Protocol require an inventory of GHGs as well as specific LULUCF CRF tables. According to Article 3.7, reports submitted by Annex I countries under the Protocol may be used to alter the amount of allowed emissions (AAUs), and national net removals from LULUCF may result in the issuance of removal units (RMUs).

The Protocol also requires Annex I countries to establish national systems to estimate emissions by sources and removals by sinks which must be consistent with accepted IPCC guidance (Article 5). Article 7 of the Protocol requires Annex I countries to submit national annual GHG inventories and regular national communications to demonstrate compliance. Article 8 mandates expert review teams to review the inventories and national communications.

The Protocol contains "Flexible Mechanisms" (CDM and JI) in Articles 6 and 12. With regards to the CDM, this means that an Annex I country can purchase long-term certified emission reductions (lCERs)[18] or temporary certified emission reductions (tCERs)[19] from new and additional sequestration activities to help meet national commitments. For CDM, credited activities only include Afforestation and Reforestation in the first commitment period. Forest Management, Afforestation and Reforestation activities are currently permissible under Activities Implemented Jointly (JI). These activities follow specific methodologies, approved by a specialised body under the Protocol. To date, these types of activities have not been common under the Kyoto Protocol, and few have been implemented. Of the 2,000 CDM projects currently registered, only 4 are forestry projects (0.2%), no LULUCF projects are listed on the JI website.[20]

The main features of the national reporting and flexible mechanism systems are described in Table 1 below.

---

[17] Of the current Annex I signatories, 22 had elected to report Forest Management, 4 to report Cropland Management, 3 to report Re-vegetation and 2 to report Grassland Management. See: http://afoludata.jrc.ec.europa.eu/events/Kyoto_technical_workshop1/presentations/m2008/Activities%20elected%20under_3.pdf

[18] "Long-term CER or lCER is a CER issued for an afforestation or reforestation project activity under the CDM which, subject to section K below, expires at the end of the crediting period of the afforestation or reforestation project activity under the CDM for which it was issued (5/CMP.1, Annex, Paragraph 1(h))". See: http://www.cdmrulebook.org/PageId/332

[19] "Temporary CER or tCER is a CER issued to project participants in an afforestation or reforestation project activity under the CDM which, subject to section K below, expires at the end of the commitment period following the one in which they are issued (5/CMP.1, Annex, paragraph 1(g))." See: http://www.cdmrulebook.org/pageid/380

[20] As of May 21, 2009

Table 1: National inventory vs. flexible mechanism-based approach to reporting terrestrial emissions and sequestration

	National inventory	Flexible Mechanisms
Name of credits produced	AAU or RMU	tCER or lCER
Entity responsible for data collection/ capacity to implement	Government	Project developer / local entity
Entity liable for under-estimations of removals, or over-estimation of emissions	Annex I Government	Annex I Government[21]
Scale	National	Defined by the project boundary: typically a contiguous block of > 100 ha, or a group of separate blocks
Frequency	Annual	Min. once every five years
Land use categories covered	Managed lands	Afforestation and Reforestation activities all within the project boundary (CDM) and also forest management for JI
Pools assessed	Recommended to measure significant sources/removals Typically only assess ABG	Required to measure all significant sources/ removals, according to relevant methodology.
Detail	High variation in level of detail between countries	Very detailed
Transparency and public scrutiny	Only one formal review, not as heavily scrutinised[22]	High level of public scrutiny and review – typically 2 formal reviews
Financial reward	Usually, there is no financial reward.	Projects are only carried out for the purpose of financial reward, although these must meet additionality criteria. Financial reward once every 5 years.

[21] It is the Government of the country purchasing the credits from the flexible mechanism that is ultimately responsible for meeting its targets under the Kyoto Protocol. A Government purchasing an lCER or tCER is responsible for replacing it at the end of the period. The Government may transfer this risk to the intermediary or project developer, but the final liability still rests with the Government.

[22] Although within the EU "bubble" AFOLU reports are also scrutinised by the Joint Research Commission (JRC) prior to submission.

1.2 IPCC guidance for reporting terrestrial carbon pools

1.2.1 How to identify what to measure

Estimating terrestrial carbon requires tracking changes in the areal extent of different land use categories (see Section 1.4) and the carbon density of these categories. The first step is hierarchical and systematic identification of key land use categories, ensuring that they are represented in a consistent manner. The IPCC recommends the following three complementary approaches[23]:

- *Approach 1* harmonizes area datasets produced for other purposes to estimate net area of land use for the various land use categories. There is no tracking of land use conversions. This results in Net-Net change estimates between land use categories;
- *Approach 2* introduces tracking of land use changes between categories and results in a non-spatially explicit land use change matrix, it results in Gross-Net change estimates between land use categories and;
- *Approach 3* tracks land use changes on a spatial basis. This approach leads to an estimate of Gross-Net changes between and within land use categories.

Following this, key land use categories within the selected sector can be identified; e.g. forest land within LULUCF sector, or savannah burning within the agriculture sector. This may be extended to selection of key sub-categories and finally to the selection of key carbon pools: aboveground biomass (ABG), belowground biomass (BGB), dead wood, litter, Soil Organic Matter (SOM), and Harvested Wood Products (HWP).

The purpose of this categorization is to facilitate the identification of priority land use classes for measurement and monitoring. The IPCC uses a hierarchical tier method to estimate uncertainties and for classifying reporting systems; tiers range from 1 to 3, depending on quality of data used and approach taken (see Table 2 below). Estimates should be accurate and uncertainties identified, quantified and reduced as far as practical. Carbon stocks of the pools considered to be significant should be estimated at the higher tiers (2-3). Existing guidance for project-based activities under the flexible mechanisms (CDM or JI) requires projects to be developed in accordance with approved methodologies and tools; the specific methodology applied then dictates which pools are measured and estimated.

1.2.2 How to estimate carbon stocks and changes

Estimates of removals and emissions would ideally be based on direct measurements of carbon flux. However these techniques are currently expensive and difficult to apply at scale[24], measuring

[23] For more information see LULUCF GPG 2003 and see presentation by Nalin Srivastava of the IPCC National Greenhouse Gas Inventories Program: "IPCC Guidelines for National GHG Inventories and Reporting for Forest Land", at World Forestry Week/19th Committee on Forestry Sessions in Rome, March 16-20, 2009. Rome, Italy.

[24] One example of such a technique is the Eddy Covariance technique which measures gases emanating from lands directly. See, for example, FluxNet which is a global network of meteorological tower sites using eddy covariance methods to measure exchanges of carbon dioxide, water vapour and energy between the biosphere and atmosphere:

changes in carbon is commonly done by estimating changes in carbon density and land use area based on inventory-type empirical approaches or net changes in each carbon pool ("process based" approach).

At the very simplest level, measurements of total terrestrial carbon stocks are a function of area (of each land use category) and carbon density (amount of carbon per unit area). Estimates of change (monitoring) are therefore repeated measurements to assess changes within and between land use categories, i.e. a carbon stock estimate combined with "activity data", the "data on the magnitude of human activity resulting in emissions or removals taking place during a given period of time"[25]. These methods are summarised in the IPCC GPG 2003[26] as well as the IPCC 2000[27] guidance (for agriculture). Carbon density is usually estimated by combining field measurements and the conversion (or allometric) equations described in the following Chapter. Changes to carbon stocks rely on the identification of changes in carbon density and / or areal extent; this information can then be used to estimate terrestrial carbon changes over the specified period of time. Information on areal extent can often be most efficiently gathered using remote sensing methods. The density and area data can be used to estimate changes over time by using models.

The type and direction of land use changes have different implications for carbon emissions and removals. For example, converting pasture land to conifer plantation may increase aboveground (ABG) biomass stocks, but decrease Soil Organic Matter (SOM)[28]. Within a given land use category, there are also changes in land management practices, that may increase or decrease stocks, e.g. changes in extraction practices in a forest. The IPCC provides detailed guidance on measuring stocks in each pool and how to measure changes in carbon as a result of land use change. Activity data for terrestrial carbon is usually associated with changes in land use and land cover, and in many cases, most efficiently collected using remote sensing (covered in Chapter 2), but can also be collected using other methods. For example:

- *Information on soil management practices, e.g. no-till or fertilizer practices*. This could be tracked by the land owner/farmer or by a multilateral agency such as FAO. It can be used as an input to soil carbon models, or used with Tier 1 emission factors.
- *Information on local forest management regimes:* This could be tracked by the forest manager / owner, or local government. It could include total volume removed, area damaged per cubic meter removed, amount of slash and damage to residual stand per

---

http://www.fluxnet.ornl.gov/fluxnet/index.cfm. Results using this technique rely heavily on measurement location representativeness. This method also requires accessing remote sites in difficult terrain, expensive preparation and equipment, access to electricity and regular maintenance.

[25] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html

[26] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html

[27] IPCC, 2000. *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html

[28] Guo, L.B., Wang M. & Gifford, R. (2007). The change of soil carbon stocks and fine root dynamics after land use change from a native pasture to a pine plantation. Plant Soil 299:251-262

volume removed, rate of re-growth in the harvested areas relative to non-harvested areas, and decomposition rates of slash.[29] It could be used to determine the impact of forest management practices, for example the residual damage from logging.

- *Maps or surveys of fire observations:* This could be tracked by local Government, and could be used to determine the impact of fire on GHG emissions.
- *Forest density classes based on the crown density:* This could be tracked by the forest survey wing of the local forestry sector. High crown density within a forest type may indicate high biomass (and carbon).

The reporting tiers used by the IPCC and summarised in Table 2 below emphasise different combinations and qualities of methods. A country may report different land use categories using combinations of methods, and therefore reporting tiers. It is recommended that a country report the most significant sources and sinks using higher tier methods.

Table 2: IPCC Reporting Tiers description[30]

Tier	Description
Tier 1	Requires no new data collection; uses default values (e.g. from the IPCC emission factor database (EFDB)). Usually uses activity data that are spatially coarse, such as estimates of global deforestation rates.
Tier 2	Uses the same approach as Tier 1, but applies country-defined emission factors and activity data. Typically uses higher-resolution activity data, to correspond with country-defined coefficients for specific regions and specialised land use categories.
Tier 3	Uses higher order methods, including models and inventory measurement systems, repeated over time and tailored to reflect national characteristics. Input is in the form of high-resolution activity data disaggregated at the sub-national level or finer, areas where land use change occurs are tracked over time. Certainty is higher and there is a closer link between biomass and soil dynamics. These systems may incorporate a climate dependency and can therefore provide estimates of inter-annual variability. Models should undergo quality checks, audits and validations. An example is a GIS-based combination of age, class/production data systems with connections to soil modules, integrating several types of monitoring.

The change in terrestrial carbon at the national level is equal to the sum of the changes within and between each of the national land use categories:

$$\Delta C_{LULUCF} = \Delta C_{FOREST} + \Delta C_{CROPLAND} + \Delta C_{GRASSLAND} + \Delta C_{WETLAND} + \Delta C_{SETTLEMENTS} + \Delta C_{OTHER\ LAND}$$

[29] USDA, 2007. Measurement Guidelines for the Sequestration of Forest Carbon USDA Forest Service, General Technical Report NRS-18. Pearson, T.R.H., Brown, S.L., and Birdsey R.A. (authors). USA.

[30] Adapted from Chapter 3 in IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html

Land use categories are sub-divided into land remaining in the same category and converted. Nation or local-specific sub-categories can be created based on climate, soil type, ecological regions or management activities. Depending on the significant category and sub-category, various pools must be accounted for. The general equation is presented below:

$$\Delta C = \Delta C_{ABG} + \Delta C_{BGB} + \Delta C_{DEAD\ WOOD} + \Delta C_{LITTER} + \Delta C_{SOM}$$

NB: *Value is zero for pools that do not have to be counted; current rules also state that reporting of carbon in HWP is separate and optional*

For monitoring periodic changes in carbon pools, the IPCC recommends the two methods summarised in Table 3 below[31]. These are summed over all land uses in the country to estimate total emissions and removals.

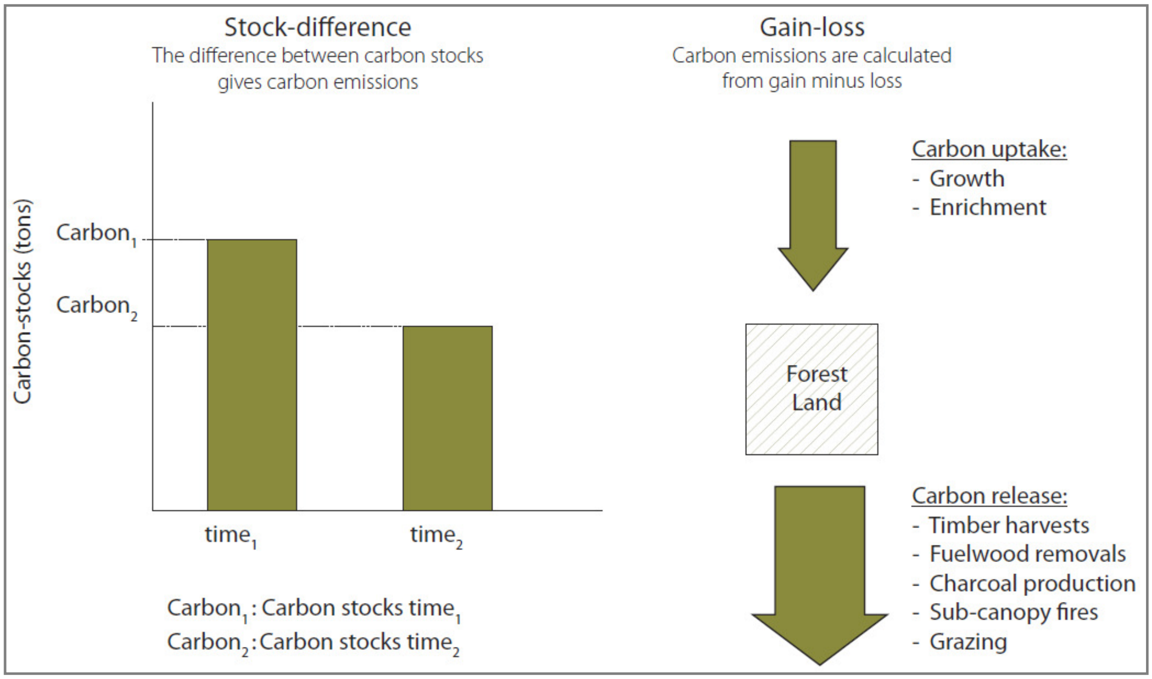
Table 3: Gain-loss vs. Stock-difference Approaches to changes in carbon density[32]

Gain-loss:	Stock-difference:
$\Delta C = \Delta C_G - \Delta C_L$	$\Delta C = (C_{t2} - C_{t1}) / (t_2 - t_1)$
ΔC = carbon stock change in pool (tonnes carbon p.a.) ΔC_G = annual gain of carbon (tonnes carbon p.a.) ΔC_L = annual loss of carbon (tonnes carbon p.a.)	ΔC = carbon stock change in pool (tonnes carbon p.a.) C_{t1}, C_{t2} = stock at time 1 and time 2 respectively t_1, t_2 = time 1 and 2 respectively
• Process based, requires models that simulate removals and additions • Accuracy and completeness depend on data and models used (Tier) • Can be used by countries without national inventory systems	• Inventory or measurement based • Requires repeated measurements over time

[32] Based on Chapter 2 in: IPCC Guidelines for National Greenhouse Gas Inventories, Edited by Eggleston, S., Buendia, L., Miwa, K., Ngara, T., and K. Tanabe, 2006, Japan. Volume 4: Agriculture, Forestry and Other Land Use. Authors: Paustian, K., Ravindranath, N.H., and A.v. Amstel. Review Editors: Apps, M., Plume, H., Schlamadinger, B. And S. N. Appadu. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

The difference between the two approaches is described further in Figure 2 below.

Figure 2: Estimating emissions from forest degradation: comparing the stock-difference and gain-loss methods[33]



1.2.3 Quality Assurance and Quality Control

In addition to providing guidance on measurement and monitoring methods, the IPCC also provides general[34] and specific guidance[35] on quality assurance (QA) and quality control (QC) procedures. These are designed to increase the quality, transparency, completeness and comparability of inventories in general, and specifically for the land use sector due to the variety of input data required (including historical data), complexity of the interactions, variability of biological processes and the magnitude and nature of data[36]. QC is "a system of routine technical activities, to measure and control the quality of the inventory as it is being developed... designed to: (i) provide routine and consistent checks to ensure data integrity, correctness and completeness; (ii) identify and address errors and omissions; (iii) document and archive inventory material and record all QC

---

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

[34] IPCC, 2000. *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html

[35] IPCC GPG 2000, Chapter 8 (*ibid)*

[36] IPCC GPG 2000, Chapter 8 (*ibid)*

activities."[37] QA activities refer to a planned system review of procedures conducted by independent experts.[38]

QA/QC procedures for the land use sector are generally required to address how land areas are represented, measurement methods and, if relevant, national accounting of emissions and removals under the Kyoto Protocol. Specific recommended QA/QC guidance depends on the Tier of reporting, but there are some generic requirements including:

- An inventory agency responsible for coordinating QA/QC activities;
- A QA/QC plan;
- General QC procedures (Tier 1) that cross-cut all inventory categories;
- Source or sink category-specific QC procedures (Tier 2) requiring knowledge of data and methods;
- QA review procedures;
- Reporting, documentation and archiving procedures.[39]

More detailed guidance on the specific requirements and procedures can be found in the IPCC GPG 2003.[40]

1.3 Classification of land uses

Prior to deciding on a sampling approach and carrying out measurements, it is essential to have an understanding of the existing land cover and use[41] – for example through classification of lands. This is both necessary, in order to understand what to sample, measure, monitor and report, and recommended by the IPCC in order to ensure consistent representation of lands, optimise use of methods[42] and reduce overlaps and omissions[43]. Furthermore, not all areas may need to be reported on, and within those that it is necessary to report on, some are of greater priority than others.

Countries and sectors may have their own mapping program, which typically reflect their priorities. This has led to a variety of mapping and classification systems that differ in detail and quality as well as in age and timing. Classification consistency is made more difficult when a variety of landscapes

---

[37] IPCC GPG 2000, Chapter 8, p. 5.49 (*ibid)*

[38] IPCC GPG 2000, Chapter 8, p. 5.49 (*ibid)*

[39] *Ibid.*

[40] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html

[41] "Land use is defined through its purpose and is characterized by management practices such as logging, ranching and cropping. Land cover is the actual manifestation of land use (i.e. forest, grassland, cropland)." From http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=132

[42] For example, the use of allometric equations is optimised when applied to the specific land use categories for which they were developed. Additionally, Remote Sensing tools also rely heavily on land use classification for interpretation.

[43] IPCC, 2000. *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.htm

are included and where there is variability within land use categories (for example both permanent and annual crops in the category "croplands").

There have, and continue to be developments in standardizing classification systems and legends (for example European CORINE[44]) and, of even greater importance, in making them comparable. The only UN-endorsed land cover classification system is the FAO/UNEP Land Cover Classification System (LCCS)[45], which is undergoing approval to become an ISO standard.

The following section describes some common sampling techniques. It is important to note that land cover maps are necessary to formulate the sampling strategy. Results from the sampling (or data collection) activities can however also be used to refine land cover maps and can therefore lead to improved land cover classification and to more consistent representation of land uses and changes over time.

1.4 Sampling methods and measurement error

Data requirements and the choice of carbon measurement approach depend on budget and scope as well as:

- Availability, accessibility, quantity and quality of existing data (to determine what information is missing, or how it might be improved)
- Spatial heterogeneity
- Purposes for which measurement and monitoring are taking place (e.g., annual reporting of carbon stocks, developing carbon credits)
- Availability of measurement or monitoring equipment

Depending on these parameters, a total population or census ("wall-to-wall" mapping), or a sample of the population can be measured and results extrapolated to infer a value for the total population. Sampling is usually a cost-effective way to obtain a representative picture of the area. Wall-to-wall and sampling approaches are not mutually exclusive: "a sampling approach in one reporting period may be extended to wall-to-wall coverage in the subsequent period."[46] Similarly, wall-to-wall mapping in one time period may produce reliable strata for a sampling approach in subsequent time

[44] For more information on CORINE, please refer to: http://www.eea.europa.eu/publications/COR0-landcover

[45] "LCCS is a comprehensive, standardized, *a priori* classification system designed to meet specific user requirements, and created for mapping exercises, independent of the scale or means used to map. It enables a comparison of land cover classes regardless of data source, thematic discipline or country. The LCCS system enhances the standardization process and minimizes the problem of dealing with a very large amount of pre-defined classes." For more information on this please refer to: Land Cover Classification System (LCCS): Classification concepts and user manual by Di Gregario, A. and L.J.M. Jansen. Environment and Natural Resources Service (SDRN), GCP/RAF/287/ITA Africover – East Africa Project and Land and Plant Nutrition Management Service (AGLN). FAO, Rome, 2000. http://www.fao.org/docrep/003/x0596e/x0596e00.htm

[46] CIFOR, 2008. *Moving Ahead with REDD, Issues, Options and Implications.* Angelsen, A., Atmadja, S., Wertz-Kanounnikoff, S., Lubowski, R., Streck, C., Peskett, L., Brown, C., Luttrell, C., Dutschke, M., Brown, J., Wunder, S., Verchot, V., Kanninen, M., Mudiyarso, D., Skutsch, M., Guariguata, M., Verweij, P., Martins, O.S., Brown, D., Seymour, F., and Guizol, P. (edited by Angelsen, A.). Indonesia. Available at: http://www.cifor.cgiar.org/publications/pdf_files/Books/BAngelsen0801.pdf

periods. A good sampling plan is vital for developing an affordable data set that is consistent over time.

The IPCC GPG 2000[47] describes sampling strategies appropriate for LULUCF. Other guidance on common sampling techniques exists in the FAO-IUFRO National Forest Assessments Knowledge Reference[48] and in the GOFC-Gold Sourcebook.[49] Key principles in the application of data collection plans are practicality, minimisation of bias and enhancement of accuracy and precision. Plans should also be transparent - this means consistently documented evidence, sampling procedures, measurement procedures (including for data interpretation) and a QA/QC plan.[50]

1.5 Existing information sources and access to existing information

Measurement and monitoring methods are described in Chapter 2. As these tend to require historical data and be based on existing data-gathering systems it is useful to review some of the existing information sources. Many countries already carry out regular measurement of terrestrial carbon stocks for national policy development and planning, particularly on above-ground woody biomass (forests). These programs may provide a useful foundation of experience and infrastructure for expanded measurement and monitoring systems. It is important to note that where existing legacy information for carbon pools does exist, it is not always reliable, comparable, and accessible.[51]

1.5.1 Existing national reports: UNFCCC-based and National inventories

As described in Section 1.1 above, Annex I countries are required to submit annual and periodic information on removals and emissions. Non-Annex I countries are required to submit periodic National Communication reports, these vary significantly in quality due to lower reporting requirements, i.e. they are encouraged rather than required to use IPCC guidelines. So far 134 out of 150 non-Annex I countries have submitted such reports, and of these only Mexico, South Korea and Uruguay have submitted a second report.[52] These reports provide useful estimates of emissions and

---

[47] IPCC, 2000. *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Available from: http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html

[48] http://www.fao.org/forestry/26364/en/

[49] GOFC-Gold, 2008. Reducing Greenhouse Gas Emissions from Deforestation and Degradation in Developing Countries: A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting, GOFC-Gold Report version COP 13-2, (GOFC-Gold Project Office, Natural Resources Canada, Alberta, Canada). Available at: http://www.gofc-gold.uni-jena.de/redd/index.php

[50] USDA, 2007. Measurement Guidelines for the Sequestration of Forest Carbon USDA Forest Service, General Technical Report NRS-18. Pearson, T.R.H., Brown, S.L., and Birdsey R.A. (authors). USA. This quality assurance program should include standardized procedures (including independent assessment or auditing procedures) for: calibrating instruments, collecting and reporting reliable field measurements, documenting and verifying lab procedures, verifying data entry, analysis techniques, data maintenance and archiving.

[51] Pers. Comm., Alfred Hartemink, ISRIC (16 March, 2009)

[52] For more information please refer to http://unfccc.int/national_reports/items/1408.php

removals for some countries and sectors, as well as background information on how the data are derived.

Several countries already have systems in place to estimate woody biomass stocks[53], e.g. National Forest Inventories (NFIs). However, many of these inventories are restricted to merchantable species and do not include information on non-commercial and non-tree species which may represent a significant portion of terrestrial carbon stocks. The frequency of measurement may also not be well suited to terrestrial carbon characteristics. There are also many parts of the tropics in particular where inventories are out of date, incomplete, or entirely lacking.[54] Additionally, the IPCC requires that the system be able to define land use in 1990 and have a relatively short update cycle[55]. For reporting purposes (Annex I) the required update cycle is typically annual, but for project-based activities, at least once every five years.

Field information collected for compiling National Forest Inventories typically includes data on:

- Forest purpose (e.g. timber, conservation etc.)
- Land cover (e.g. information on area of forest),
- State of the forest in terms of succession stages, canopy cover, diameter classes (for example using diameter at breast height (DBH), height, form factor and basal areas) and degradation
- Forest health (fires, perturbations)
- Silvicultural operations (e.g. thinning, slash removal etc.)
- The survey may also gather information on land tenure, local social conditions and conflicts, where applicable

NFIs differ significantly in terms of definitions, variables included, standards applied and technical quality. Two examples of national-level inventories are provided in Annex II. Some countries, regions or states also have their own land-use reporting requirements e.g. the State of California.

Little is typically recorded for non-forest biomass except through agricultural yield statistics[56] and annual agricultural census.

This existing information can be a useful starting point for estimating carbon stocks, if species density is known, and to develop estimates of total biomass when Biomass Expansion Factors (BEFs) are available (see Chapter 2 below).

---

[53] See: Holmgren, P., Marklund, L-G., Saket, M. & Wilkie, M.L. 2007. Forest Monitoring and Assessment for Climate Change Reporting: Partnerships, Capacity Building and Delivery. Forest Resources Assessment Working Paper 142. FAO, Rome (ftp://ftp.fao.org/docrep/fao/010/K1276E/K1276E00.pdf)

[54] Houghton, R.A. “Aboveground Forest Biomass and the Global Carbon Balance.” Global Change Biology, 11 (2005), 945-958. Available at: http://www.whrc.org/resources/published_literature/pdf/HoughtonGCB.05.pdf

[55] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe K. and Wagner, F. (eds). Japan. Available at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html

[56] T12 Biomass Background (Reuben Sessa, FAO NRDC)

1.5.2 Commercial assessments

Commercially managed land areas often have comprehensive records related to management, timber stock, harvest rates and other relevant information. These may be used to compare with national inventories to estimate accuracy or used to extrapolate other results.[57] In some cases, silvicultural analyses, or company wood production data may be used to estimate carbon or biomass stocks, and accumulation rates. Commercial assessments can help to determine changes in land use classes. An issue, however, may be confidentiality or the commercial sensitivity of this information, as it is also used to value the company owning the timber or crop. Availability of commercial information may be lacking in areas with a short history of (formal) commercial forest management, and is closely linked to the sensitive issue of tenure, land ownership and transparency.

1.5.3 Academic scientific assessments

Academic studies, in particular long-term study plots, may provide useful information on carbon or biomass stocks and changes in stocks over time. They may also be used to develop more specific local models or equations and to ground-truth remote sensing data. This type of data may for example yield site specific allometric equations developed from destructive sampling which can be used to interpret other measurements.

1.5.4 Other information sources

Existing compliance and voluntary-market projects often develop project-level inventories which collect field-data along with other social or environmental indicators.[58] Such information may be useful to incorporate into a national estimate of stocks and changes.

A number of other data collection initiatives also exist and are under development. A non-exhaustive table describing some of these initiatives is provided in Annex III.

[57] USDA, 2007. Measurement Guidelines for the Sequestration of Forest Carbon USDA Forest Service, General Technical Report NRS-18. Pearson, T.R.H., Brown, S.L., and Birdsey R.A. (authors). USA.

[58] Pers. Comm. Jacqueline Gehrig-Fasel, Perspectives (2 April, 2009)

2 TERRESTRIAL CARBON MEASUREMENT: METHODS

This Chapter describes the different but complementary types of measurement methods that can be used to estimate terrestrial carbon, focussing on ABG biomass. In this report, we refer to "field measurements" as those done in-situ and converted into biomass and carbon estimates using conversion (allometric) equations[59]. The term "remote sensing" is applied to techniques that use optical, radar or lidar sensors mounted on aircraft or space-borne platforms. Information from data collected using remote sensing is typically interpreted using field estimates.[60] Repeated measurements over time (monitoring) is necessary to assess change. This is done using a combination of field methods and remote sensing. Results can be combined with other types of data (e.g. information on land management) and fed into models to estimate current stocks as well as changes.

Table 4 below summarises the various categories of complementary methods to measure terrestrial carbon.

Table 4: Methods for measuring terrestrial carbon

	What can it do?	Pros	Cons
Field Measurements and Observations	Carbon density, areal extent, change over time if measured more than once	• Precise for measured variable, • Low technology requirement • Can be inexpensive depending on labour cost	• Costs related to labour and area, • Limited to measurable variables, • Can be slow, • May not provide results that are consistent over a large area • Accuracy may depend on conversion values applied

59 In this report we refer to the term "allometric equation" as a more specialised form of conversion equation, providing a mathematical comparison of how characteristics of different organisms of the same species compare, and also between organisms in different species. For more information see: Avery and Burkhart. Forest Measurements. Copyright 2002 by McGraw-Hill Companies Inc. New York.

60 Carbon density estimates are obtained using field measurement methods. Although new types of remote sensors can estimate density, these are not yet well-tested and widely applied.

	What can it do?	Pros	Cons
Remote Sensing	Areal extent, volume and change over time if measured more than once.	• May be cost-effective, • Supports field work performance, • Transparent interpretation methodologies, • Can be routinely collected, if available, • Globally consistent, • Accurate for area estimation	• Some forms of sensor may not be suitable for tropical forests, • Can be technically demanding, can be expensive to interpret results • Not all forms of remote sensing is available for all regions • Not suitable for estimating stocks.
Models	Combine information to derive carbon volumes	• Framework for integrating various types of data	• Dependent on quality of input data.

2.1 Field methods

2.1.1 Field measurements: Above and below-ground live biomass

Depending on method and available allometric equations, biophysical field measurements can result in the most accurate measurements. Field measurements can be gathered using a variety of sampling techniques, ranging from fixed area plots, variable radius or point sampling plots or transects.[61] These measurements are converted into carbon estimates by applying specific or default values and relationships (allometric equations) to the oven-dried weight of biomass.[62] An overview of ABG biomass measurement methods are provided in Table 5 below. Methods are purpose-specific and complementary. Destructive methods, for example, provide information necessary to calibrate models or derive allometric equations.

---

[61] For more information, please refer to IPCC GPG LULUCF 2003

[62] USDA, 2007. Measurement Guidelines for the Sequestration of Forest Carbon USDA Forest Service, General Technical Report NRS-18. Pearson, T.R.H., Brown, S.L., and Birdsey R.A. (authors). USA. For appropriate, accepted default value refer to the IPCC EFDB.

Table 5: Destructive and non-destructive methods to measure ABG biomass

Method	Description	Some sources of uncertainty
Destructive methods	Harvest tree (and/or other living aboveground material such as random branches[63]) and determine biomass through actual weight of all components (stem, branches, and foliage). This is the most accurate method within a small unit area, but it is expensive, time consuming, damaging to the environment and infeasible at large scale.[64] It is mostly used to calibrate allometric equations.	• Morphological variations • Species identification • Representativeness of the plot • Variability due to the application of allometric equations (described under the following sub-heading)
Non-destructive methods[65]	*Allometric methods*: Conduct a field inventory, where data are collected at plot level on species or site-specific factors (species, stem density, DBH, height etc.) and apply appropriate equations or models to convert these measurements into biomass estimates. Typically, the more site-specific variables that are measured at site, the more accurate the biomass estimate will be.[66] It is good practice to cross-check conversion equation with some destructive sampling.	

2.1.2 Allometric equations and other regression equations used to estimate stock

Allometric[67] equations are used to estimate biomass stocks from field measurements (DBH and H), or to estimate below ground (root) biomass. For example, an allometric equation for the relationship between tree diameter and total tree mass is developed by destructively harvesting a sample of trees across a representative range of diameter classes. Then the diameter of the trees can be measured, and the formula applied to estimate total mass of the trees in the area.

[63] Samalca, I. K., de Gier, A., and Hussin, Y. A. “Estimation of tropical forest biomass for assessment of carbon sequestration using regression models and remote sensing in Berau, East Kalimantan, Indonesia.” Paper presented at Asian Association on Remote Sensing (2007). Available at: http://www.aars-acrs.org/acrs/proceeding/ACRS2007/Papers/PS2.G2.3.pdf

[64] WMO, UNESCO, UNEP, ICSU, FAO, 2008. GTOS 67, ECV T12: Biomass, Assessment of the status of the development of standards for the Terrestrial Essential Climate Variables (Draft Version 8). Avitabile, V., Marchesini L.B., Balzter, H., Bernoux M., Bombelli A., Hall R., Henry M., Law B.E., Manlay R., Marklund L.G. and Shimabukuro Y.E. (contributing authors), Sessa, R. (coordinator). Italy.

[65] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe K. and Wagner, F. (eds). Japan. See: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp4/Chp4_3_Projects.pdf

[66] USDA, 2007. Measurement Guidelines for the Sequestration of Forest Carbon USDA Forest Service, General Technical Report NRS-18. Pearson, T.R.H., Brown, S.L., and Birdsey R.A. (authors). USA.

[67] Allometry refers to the “relation between the size of an organism and the size of any of its parts, an allometric equation is usually expressed in power-law form or in logarithmic form”. [67]

Default values and allometric equations are typically available for many popular commercial species or species groups, although the literature is inconsistent or incomplete for many species even within Annex I countries. In the cases where site-specific equations do not exist, it is possible to use an average equation.[68] It may be difficult to estimate the level of error associated with applying these generalized equations to a stand however, as this depends on the similarity of the stand to that on which the equation was developed.[69] The uncertainty is heightened in species diverse areas. Generally, the broader the equation in geographic scope and species included, the greater the uncertainty.

Even where relevant default equations do exist, they may have an inherent accuracy associated with them. For example, in the case of root to shoot ratios, recent studies have shown that current default ratios significantly underestimate global BGB biomass volumes, and therefore global terrestrial carbon volumes.[70]

The table below summarises some common types of conversion equations that can be applied individually, or in combination: [71]

Table 6: Common types of conversion equations

Type	Purpose	Example
Dry wood density	To convert volume of wood (m^3) to dry weight (tons) of wood	Dry weight of wood biomass
Biomass conversion factor	Converting volume and measurement estimates into biomass.	Root to shoot ratio
Expansion factor	To expand from a certain amount (volume or biomass), which includes some tree components, to another one that includes more or all tree components. Some only pertain to the ABG fraction; others pertain to both ABG and BGB.	Volume expansion factor, biomass expansion factor (BEF)
Carbon fraction	To convert from biomass (tons dry weight) to amount of carbon (tons Carbon)	Carbon content in forest biomass
Water content	To convert the fresh biomass weight into a common dry mass of the biomass	Dry weight of biomass

[68] USDA, 2007. Measurement Guidelines for the Sequestration of Forest Carbon USDA Forest Service, General Technical Report NRS-18. Pearson, T.R.H., Brown, S.L., and Birdsey R.A. (authors). USA.

[69] Gower, S.T., Kucharik, C.J. and Norman, J.M. "Direct and indirect estimation of leaf area index, fpar, and net primary production of terrestrial ecosystems." Remote Sensing of Environment, 70 (1999), 29-51.

[70] See Mokany, K., Raison, R.J., Prokushkin, A.S. Critical analysis of root: shoot ratios in terrestrial biomes. *Global Change Biology*. 2006; 12: 84-96 and Robinson, D. Implications of a large global root biomass for carbon sink estimates and for soil carbon dynamics. *Proceedings of the Royal Society of Biological Sciences*. 2007; 7: 2753-2759

[71] Adapted from: CarboInvent, 2005. "Multi-source inventory methods for quantifying carbon stocks and stock changes in European forests, Summary report of WP2." Available from: http://www.joanneum.at/carboinvent/WP_02_summary.pdf

There have been several attempts to develop international, regional or national databases of conversion factors. Examples of these include the IPCC's Emission Factor Data Base (EFDB)[72], the European Allometric Biomass Carbon factors database (ABC database)[73] and the World Agroforestry Centre's Wood Density Database[74]

2.1.3 Field measurements: Other carbon pools

The litter and dead wood pools are typically measured using an appropriate sampling method, and results extrapolated for the area. These methods are not covered in this report, but detailed guidance is available.[75] Further work is being done on the potential for application of models to estimate these pools.[76] Measuring samples from both the litter and the dead wood pools can be done as part of the data collection for the biomass pools.

To assess carbon in mineral soils, soil depth and texture is required. Additionally, care must be taken that an equivalent mass of soil is measured from one measurement event to another. This is related to soil bulk density, which may not be available for the site. Appropriate depth for soil sampling varies depending on land use type and local conditions. For example, vegetation in grasslands, peat lands and savannahs may require sampling to greater depths than other systems – under all circumstances, sampling depth must capture all management induced changes.[77]

The table below summarises some of the other methods to measure below ground carbon on mineral soils.

Table 7: Destructive and non-destructive methods for measuring SOM

Method	Description
Destructive methods	*Loss on Ignition:* Measurement of sample weight change after oven-drying. This can over-estimate SOM as, depending on the ignition temperature and sample size, the inorganic components of the sample may also change in weight during the heating process so they should also be measured.[78]
	CO_2 Combustion Analysis: Measurement of CO_2 emitted from oxidation of organic

[72] http://www.ipcc-nggip.iges.or.jp/EFDB/main.php

[73] http://afoludata.jrc.ec.europa.eu/v2007/DS_Free/abc_intro.cfm

[74] http://www.worldagroforestry.org/af2/index.php?q=node/109

[75] For example see: Harmon, M.E. and Sexton, J., 1996. "Guidelines for measurements of woody detritus in forest ecosystems". Available from: http://andrewsforest.oregonstate.edu/pubs/webdocs/reports/pub2255.pdf

[76] See, for example: Paul, K.I. and P.J. Polglase "Prediction of decomposition of litter under eucalyptus and pines using the FullCAM model" in Forest Ecology and Management, Volume 191, Issues 1-3, 2005. Pages 73-92

[77] Pers. Comm. Peter Manning, Imperial College London (25 March, 2009).

[78] Gehl, R.J. and Rice, C.W. "Emerging technologies for *in situ* measurement of soil carbon." Climatic Change, 80 (2007), 43-5

	carbon. Instrument error associated with dry combustion auto analyzers are <0.1%, overall lab measurement error using proper protocols is 1-2%[79]. This method measures total carbon, not organic carbon. Inorganic carbon should be removed from soil before analysis or measured separately for correction of organic carbon.
	Walkley-Black acid digestion[80]: Uses chromic acid to measure oxidizable organic carbon in the soil. Inaccurate for soils with high contents of very stable carbon (e.g. Black Carbon).
	New methods: Analytical pyrolysis
Non-destructive methods	*Spectroscopy*: Mid and near-infrared reflectance spectroscopy (MIR and NIR) to be utilized for measuring soil organic carbon (hand held or in the lab) in conjunction with dry combustion analyses. Is much less costly than traditional methods, and greatly increases speed of analysis.[81] These techniques are beginning to become commercially viable and can be integrated into farm equipment.[82]
	Inelastic Neutron Scattering (INS): This is not yet commercially viable.

The current default method for HWP[83] is to assume full and instant oxidation (i.e. carbon loss) of the biomass at the time of harvest. Annex I countries may choose to report storage in carbon forest products in their national inventory where they can document that these products are increasing.[84] Accepted guidelines can be found in the IPCC 2003 GPG.[85]

2.1.4 Field measurements: Experience, evaluation and application

Measurements done in the field are an essential component of measurement and monitoring systems. This type of information is required both to interpret carbon stock and changes (e.g. allometric equations), remote sensing data, and as inputs to models. Allometric equations and default values which can be used to estimate biomass and carbon do exist, but only for certain countries, forest types and species. Field measurements may also provide information that is useful for more than just national reporting of GHG emissions from terrestrial sources, including information;

[79] FAO, 2008. "Enabling agriculture to contribute to climate change mitigation, a submission by the Food and Agriculture Organization of the United Nations." Available from: http://unfccc.int/resource/docs/2008/smsn/igo/036.pdf

[80] Gehl, R.J. and Rice, C.W. "Emerging technologies for *in situ* measurement of soil carbon." Climatic Change, 80 (2007), 43-54

[81] Pers. Comm., Alfred Hartemink, ISRIC (16 March, 2009)

[82] Pers. Comm., Johannes Lehmann, Cornell University (25 March, 2009)

[83] This pool includes wood and paper products, and excludes biomass left at harvest site

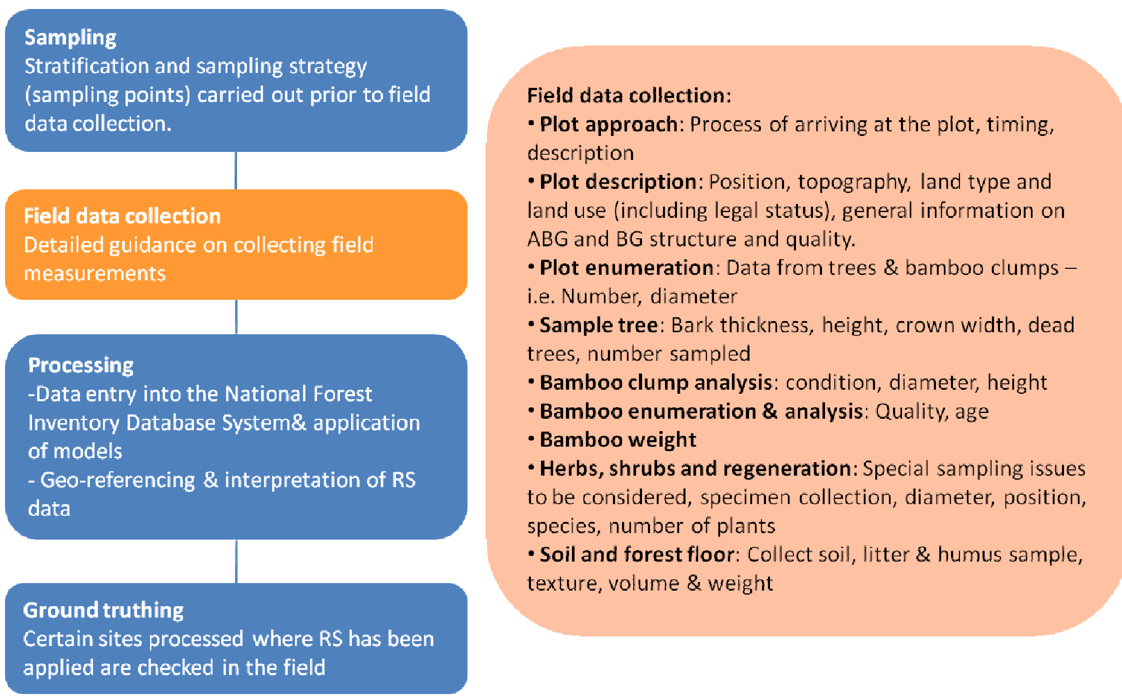
[84] See: http://unfccc.int/methods_and_science/lulucf/items/4015.php

[85] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe K. and Wagner, F. (eds). Japan. See: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp4/Chp4_3_Projects.pdf

- On vulnerability and adaptation, for example, fire risk;
- Necessary for evaluating land-use investments;
- Required for national policy formulation and planning.

There is considerable experience with field methods to quantify biomass, in particular above-ground biomass in tropical, temperate and boreal regions. Biomass measurement and monitoring methods are typically commonly-accepted and widely practiced, and often require basic technical capacity. The largest cost of most of these methods is typically labour cost. The primary challenge is usually ensuring good, transparent data quality collection and interpretation methods that are consistent over time. A simplified example of a currently used forest inventory-related field data collection system is summarised in Figure 3 below.

Figure 3: Highly simplified diagram of "Forest Survey of India", focussing on field data collection



Adapted from: http://www.fsi.nic.in/forest_inventory.htm and http://www.fsi.nic.in/pdf/MANUALFORESTINVENTORY.pdf

2.2 Remote sensing

This section deals with the collection of data using optical, radar or lidar (laser) sensors mounted on aircraft or space-based platforms used individually or in combination. Remote sensing captures spectral and spatial characteristics of an area and may therefore be an efficient method to estimate vegetation cover, as well as density and structure.[86] The benefits of these methods are that they can

[86] Natural Resources Canada, Canada Centre for Remote Sensing: Tutorial: Fundamentals of Remote Sensing Applications, Land Cover / Biomass Mapping: http://www.ccrs.nrcan.gc.ca/resource/tutor/fundam/chapter5/20_e.php

produce spatially-explicit information at various scales, ranging from < 1m (aerial photography) to 180 km[87] and that they can collect information in inaccessible areas and may allow for repeated coverage.[88] There are a number of different sensor types (see Tables 8 and 9 below), each with its own benefit and limitation, as well as a suite of different data classification and interpretation methods.

One point to note is that this section deals with the most typical and well-tested methods. The pace of technology development in this field is fast therefore this summary may not fully capture some of the newer operational methods for automated mapping of biomass cover.

2.2.1 How does it work?

The raw "data" from remote sensing are in the form of microwave, optical or infrared radiation reflected or scattered back by the imaged area in the direction of the sensor. Sensors differ in terms of measured wavelengths; energy source, resolution (spectral, spatial, radiometric and temporal resolution), costs and data interpretation requirements (see Tables 8 and 9). For example, passive sensors detect natural radiation (i.e. sunlight) whereas active sensors emit their own energy and use this to infer characteristics about the area.

2.2.2 Estimating land use change

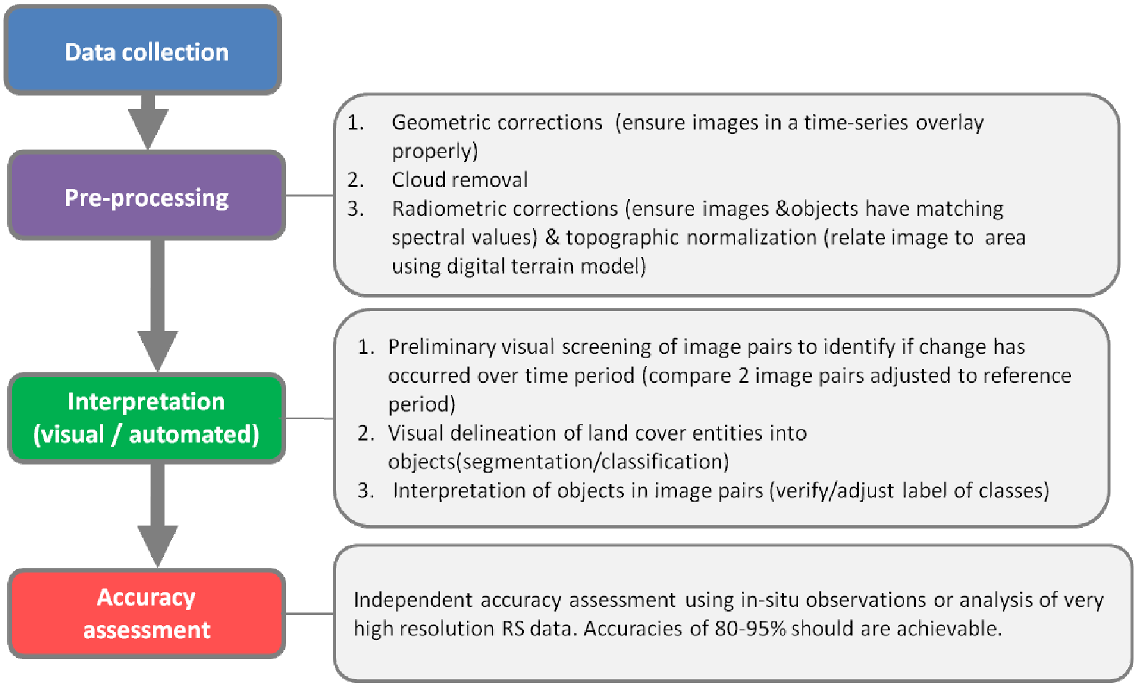
Remote sensing has been used to record land use and land cover change for several decades. In particular, remote sensing is well-suited to capturing large scale (deforestation) events. Measurement of smaller scale events (i.e. degradation and intensification or agricultural changes) requires more detailed data and data interpretation, including more intensive non-destructive field measurements.

The diagram below provides a simplified overview of the steps to collect, pre-process, interpret/classify and assess remote sensing data. Figure 5 below, is an overview of the two classification approaches used to interpret the data.

[87] Olander, L.P., Gibbs, H.K., Steininger, M., Swenson, J.J. and Murray, B.C. "Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods." Environmental Research Letters, 3 (2008). 1-11.

[88] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe K. and Wagner, F. (eds). Japan. Available at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html

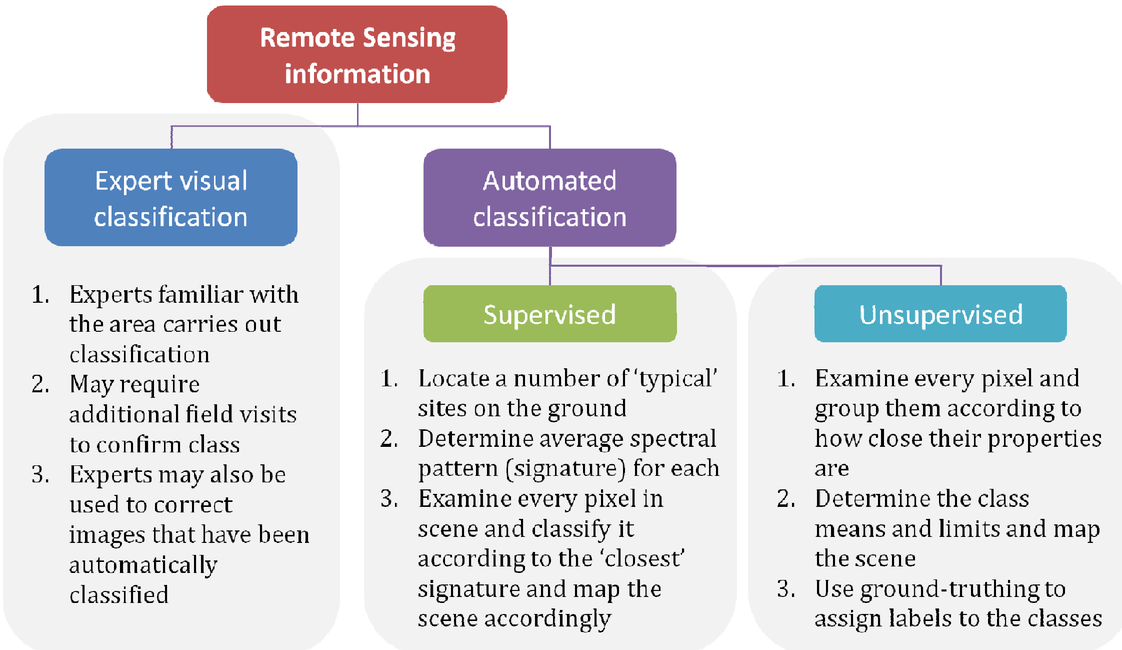
Figure 4: Remote sensing steps and potential sources of error[89]



Classification and interpretation may either be visual (carried out by experts familiar with the area) and / or automated. The figure below provides an overview of these different complementary options.

[89] Adapted from: GOFC-Gold, 2008. Reducing Greenhouse Gas Emissions from Deforestation and Degradation in Developing Countries: A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting, GOFC-Gold Report version COP 13-2, (GOFC-Gold Project Office, Natural Resources Canada, Alberta, Canada). Available at: http://www.gofc-gold.uni-jena.de/redd/index.php

Figure 5: Classification / interpretation of remote sensing images



Unsupervised classification facilitates rapid mapping, but with little or no quality control. Supervised classification results in more accurate results, but often requires substantial staff training. Adequate ground truthing is required to minimize classification errors. Common problems include: Incorrect or no geometric and radiometric correction; the pixel location and the actual location do not coincide; insufficient accuracy in the definition of borders.[90] Even when correctly calibrated, some land cover and land use classes may be spectrally inseparable using image bands available. The image interpretation process can be complex, or relatively simple, depending on the chosen procedure. Higher accuracy might be achieved by using finer-resolution imagery, imagery repeated over time or imagery requiring higher level of expertise to analyze.[91]

2.2.3 Estimating carbon density and changes in density

There are several ways that remote sensing imagery can be used to estimate carbon density and changes in carbon density. It can be estimated directly based on quantifiable relationships between biomass and spectral responses or it can be estimated indirectly based on classification techniques,

[90] IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe K. and Wagner, F. (eds). Japan. Available at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html

[91] CIFOR, 2008. *Moving Ahead with REDD, Issues, Options and Implications.* Angelsen, A., Atmadja, S., Wertz-Kanounnikoff, S., Lubowski, R., Streck, C., Peskett, L., Brown, C., Luttrell, C., Dutschke, M., Brown, J., Wunder, S., Verchot, V., Kanninen, M., Mudiyarso, D., Skutsch, M., Guariguata, M., Verweij, P., Martins, O.S., Brown, D., Seymour, F., and Guizol, P. (edited by Angelsen, A.). Indonesia. Available at: http://www.cifor.cgiar.org/publications/pdf_files/Books/BAngelsen0801.pdf

indices and regression equations or models developed through research pairing field measurements with remote sensing reflectance measurements.[92]

Combining remote sensing data with carbon density data to estimate carbon stocks in an area

To derive a map of the biomass stock over a large area, a value is assigned to each separate class (land use class or vegetation type / cover) of remotely sensed data, which is then multiplied by the estimated above and below-ground biomass stock per unit of area. In order to measure change (monitoring), updates of the remotely sensed data are compared to the baseline dataset; each pixel is classified using an algorithm to determine what type of vegetation cover (forest cover/non-forest cover) exists, and density change from the baseline year. [93] Heterogeneity of estimates across space and time within each class, and the ambiguity or incomparability in definitions of classes and representativeness of field-level data are key limitations for estimating stocks using this method.[94]

Typically, the more accurately defined the classes are, the higher the level of accuracy. The method can also be refined by using finer, dynamic, maps (e.g. using GIS) resulting in smaller units over which to overlay the field measurement. Weights can also be added to data layers to capture known heterogeneity. This type of refinement depends on the availability of field measurements that are representative of the larger area. A more complicated and technical approach, but one producing less error, is to calibrate remote sensing data directly with field estimates using “machine learning techniques”.[95]

Using remote sensing directly to make inferences about carbon stock

It is possible to directly estimate key characteristics of vegetation using newer types of sensors (radar and laser). Laser (lidar) sensors are able to measure the 3D vertical structure which can be used in allometric models to infer carbon stocks. Radar-based systems can measure surface roughness, vegetation canopy structure, topography as well as surface (including soil) moisture. Information gathered using radar-based sensors can also be used with existing allometric models to estimate carbon stock. Radar and lidar technologies have developed in leaps and bounds in the last few years and are, in some cases efficient, measurement tools. They do however still rely heavily on the quality of data and models used for interpretation. Benefits and drawbacks are summarised in Tables 10 and 11 below.

---

[92] WMO, UNESCO, UNEP, ICSU, FAO, 2008. GTOS 67, ECV T12: Biomass, Assessment of the status of the development of standards for the Terrestrial Essential Climate Variables (Draft Version 8). Avitabile, V., Marchesini L.B., Balzter, H., Bernoux M., Bombelli A., Hall R., Henry M., Law B.E., Manlay R., Marklund L.G. and Shimabukuro Y.E. (contributing authors), Sessa, R. (coordinator). Italy.

[93] See: Turner, B. (ANU) and van Laake, P. (ITC). Presentation: “How to measure carbon in different classes of biomass and different categories of forest.” (28 – 30 October, 2008). Hanoi. Available from: http://www.recoftc.org/site/index.php?id=685

[94] The Woods Hole Research Center (1-12 December, 2008). Paper developed for the UNFCCC COP, 14th Session, Poland: “How to Distribute REDD Funds Across Countries? A Stock-Flow Mechanism.” Cattaneo, A. (author). US.

[95] Ibid.

2.2.4 Estimation of non-biomass pools

Dead wood, litter and harvested wood products are generally not measured using remote sensing methods, but estimated using known relationships (LAI, NPP, crop yields and litter cover) with above-ground biomass. [96]

Estimation of SOM using remote sensing has relied on the strong relationship between the quantity of SOM and soil colour (visible reflectance). The more direct visible reflectance method of estimating SOM requires visibility of bare ground. As with remote sensing of ABG biomass, good calibration and ground truthing are essential.[97] There are limitations for estimating SOM based on soil reflectance which is a function of many factors in addition to organic matter, including soil moisture, texture, chemical composition, parent material and surface conditions. Complications are magnified when it is necessary to map a large geographical area. Ground penetration radar and other techniques have also been used to estimate soil carbon stocks.

Two examples of how remote sensing methods are used in practice are provided in Appendix IV. This is a rapidly advancing field, and many more experiences exist that are not included. The example from Canada (EOSD) shows how remote sensing methods are integrated with other methods to provide a high quality inventory. Another example is the ECHIDNA sensor, which may in the future provide higher-precision information from lidar sensors.

---

[96] Izaurralde, C.R. (PNNL, Joint Global Change Research Institute) and Rice, C.W. (Kansas State University). Presentation: "Methods for Measuring and Monitoring Soil Carbon Sequestration." (2 March, 2009). World Bank Soil Carbon Methodology Workshop. USA.

[97] Gehl, R.J. and Rice, C.W. "Emerging technologies for *in situ* measurement of soil carbon." Climatic Change, 80 (2007), 43-54

Table 8: Different sensor resolutions, importance and costs

Term	What does it mean?	Why is it important?	Examples	Cost
Coarse resolution	Relatively little ability to differentiate individual structures, typically indicates a spatial resolution of ≥ 250m	Used to identify relatively homogenous land use classes and identify areas where more field measurements might need to be carried out (and help develop a sampling strategy), identify biomass change hotspots or locations of rapid change (frequent coverage overcomes cloud cover, can identify hotspots for more detailed analysis). Typically acquired globally and routinely archived at high temporal frequency (e.g. daily). Image processing can be automated and completed quickly for rapid assessment.[98]	AVHRR, Terra-MODIS, Envisat-MERIS, SPOT-VGT	Free
Medium resolution	More ability to differentiate individual structures, spatial resolution of 5 – 250m	Used to identify/measure deforestation, may detect some forms of degradation. Possible to conduct regional/country scale assessments. Globally pre-processed landsat available.[99]	SPOT, Landsat-MMS, TM or ETM+, Terra-ASTER, IRS LISS III or AwiFs, CBERS HRCCD, DMC, SPOT-HRV, ALOS/ PALSAR, DMC	From 0 (free) to €0.02 per km^2 (wall-to-wall for a country: > €10k, sample: > €3K[100])
Fine resolution	Spatial resolution of items on the ground to ≤ 5m	Used for very small areas as otherwise too costly (e.g. for validation or verification). Typically enables discrimination of individual trees. Used to calibrate algorithms for analyzing medium and coarse resolution data and also help to verify results (increase accuracy). Fine resolution data increases the amount of data to be processed, and is therefore associated with an increase in financial and capacity requirements[101].	Aerial photos, JERS IKONOS, QuickBird, SPOT-5	For recent pictures € 2-33 per km$^{2.}$ Wall-to-wall for a country: €1-15m, for a sample: €~250k[102]

[98] Olander, L.P., Gibbs, H.K., Steininger, M., Swenson, J.J. and Murray, B.C. “Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods.” Environmental Research Letters, 3 (2008). 1-11.

[99] Ibid.

[100] Adapted from: Achard, F. (Joint Research Centre). Presentation given at UNFCCC Workshop, Rome: “Remote sensing and data availability: Measuring deforestation & degradation in the Tropics using Earth Observation techniques.” (31 August 2006).

[101] Sánchez-Azofeifa, G.A., Castro-Esau, K.L., Kurz, W.A., and Joyce, A. “Monitoring carbon stocks in the tropics and the remote sensing operational limitations: from local to regional projects.” Ecological Applications, 19(2), (2009), 480-494.

[102] See: Achard, F. (Joint Research Centre). Presentation given at UNFCCC Workshop, Rome: “Remote sensing and data availability: Measuring deforestation & degradation in the Tropics using Earth Observation techniques.” (31 August 2006).

Table 9: Overview of different sensor types

Name	Examples	How it works?	Platform	Benefits	Drawbacks	Accuracy	Cost	Capacity
Synthetic Aperture Radar (SAR)	ALOS Palsar, ERS-1, JERS-1, Envisat/ASAR, RADARSAT ½, TerraSAR-X, Cosmo/SkyMed, , BIOMASS, Tandem-X, MAPSAR	Transmit microwave energy and measure time delay and intensity of reflected energy	Satellite and airborne	Suitable for night/smoky or cloudy conditions Potentially useful for measuring vegetation height or canopy structures. Can provide frequent information. May be able to enhance other data options, but not sufficient by itself.[103]	Less accurate for complex canopies/ mature forest and for differentiating between primary and secondary growth. Not yet accessible to broader community. Can be affected by soil moisture. Requires high level of expertise, and may not work well in mountainous regions.[104]	M	H	H
Light Detection and Ranging (lidar)	Optech ALTM series, Leica ALS series, (space borne, many aircraft mounted systems in operation)	Emits pulses of laser energy and measures how long it takes for the pulse to be reflected back.	Air-craft (space-borne in research phase for biomass applications)	Direct spatial measurement. Measure vegetation height/structure and terrain in detail. Precise if well-calibrated (tens of cm). Can be operated day or night.	Cannot penetrate cloud cover. Expensive to acquire and process. Precision can be affected by crown shape; it is also dependent on scan density and flying height. Requires additional staff capacity. Most trial information to date is proprietary. Only provides local coverage.	H	H	H

[103] Olander, L.P., Gibbs, H.K., Steininger, M., Swenson, J.J. and Murray, B.C. "Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods." Environmental Research Letters, 3 (2008). 1-11.

[104] Ibid.

Name	Examples	How it works?	Platform	Benefits	Drawbacks	Accuracy	Cost	Capacity
Passive Optical	Landsat, Aster, SPOT, MERIS, MODIS, IRIS	Passive sensing of visible and near-infrared (and in some cases, short-wave infrared (SWIR)) reflectance.	Satellite	Routinely and systematically collected, globally consistent, may be used to identify where changes are occurring. Best for land cover mapping. Mature technology.	Limited availability to develop good models for tropical forest, Spectral indices based solely on red and NIR ratios saturate at high biomass. Vegetation indices incorporating SWIR may be more appropriate at high levels of live biomass. MODIS may be more suitable to national level monitoring.	M/L	L	H
Very High Resolution (VHR) sensors	Aerial photography, IKONONS, QUICKBIRD	Passive sensing of visible and near-infrared reflectance	Satellite/ Air-craft	Well suited to forest stratification for optimising sampling strategies. Can be used for individual tree inventories (e.g. total stocking estimates and individual crown condition). Local variance algorithms applicable to infer structural complexity, such as growth stage. Easy to interpret manually (visually). Good validation tool, and can be used to detect degradation.[105]	Unable to penetrate cloud/smoke. Covers very small areas, country coverage not available, demanding to process, only collects targeted or tasked locations.[106]	H	M/H	H

[105] Ibid.

[106] Olander, L.P., Gibbs, H.K., Steininger, M., Swenson, J.J. and Murray, B.C. “Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods.” Environmental Research Letters, 3 (2008). 1-11.

2.2.5 Remote sensing: Evaluation and application to estimating carbon

The table below provides an overview of some of the strengths and limitations of using remote sensing to measure and monitor terrestrial carbon. In order to maximise the use of remote sensing the data should be updated relatively frequently, credible, and systematic with global and free/open access.[107]

The most suitable type of sensor depends on the necessary resolution (see Table 8) and the size of the area to be measured. For example, will the information be used to decide where to carry out field measurements, or will it be used to gather precise, time-sensitive information on certain crop management activities?[108] It also depends on the type of sensor information that is available for a given area or region, and on the quality of the associated ground observations. There are many choices, and there is a need to optimise among spatial, spectral and temporal resolution, availability, continuity, cost[109] and technical skills required for analysis. Typically, the smaller the Minimum Mapping Unit (MMU), the higher the accuracy, but cost and effort to interpret are also significantly higher. It may therefore be efficient to use both coarse and fine resolution remote sensing in combination.

More recently, the field of remote sensing is taking advantage of fusion across different sensors to approximate areal extent, surface structure, and dynamic processes in ways that have not been feasible before. These applications are an advanced use of remote sensing data that will enhance land surface monitoring capability. However, estimates generated to meet compliance obligations (e.g. for carbon offset projects) depend on objectives and on the land use classes included in the obligations. A range of REDD mapping methods are currently available, and are being distributed and tested in a variety of countries such as Peru, Bolivia, Ecuador and Brazil.[110] The applicability of methods has also recently been evaluated by a number of authors, including Herold (2009)[111] and LTS International (2008).[112]

---

[107] Pers. Comm., Matt Hansen, South Dakota State University (8 April, 2009)

[108] Natural Resources Canada, Canada Centre for Remote Sensing: Tutorial: Fundamentals of Remote Sensing Applications, Land Cover / Biomass Mapping: http://www.ccrs.nrcan.gc.ca/resource/tutor/fundam/chapter5/20_e.php

[109] Sánchez-Azofeifa, G.A., Castro-Esau, K.L., Kurz, W.A., and Joyce, A. "Monitoring carbon stocks in the tropics and the remote sensing operational limitations: from local to regional projects." Ecological Applications, 19(2), (2009), 480-494.

[110] For example: PRODES-INPE in Brazil (see http://www.inpe.br/ingles/index.php) and the Carnegie Landsat Analysis System Lite (CLASlite) (see: http://www.ciw.edu/ and Asner, G.P., Knapp, D.E., Balaji, A., and G. Paez-Acosta. "Automated Mapping of Tropical Deforestation and Forest Degradation: CLASlite", courtesy of Dr. Asner.

[111] Herod, M. "An assessment of national forest monitoring capabilities in tropical non-Annex I countries: Recommendations for capacity building" prepared for The Prince's Rainforest Project and The Government of Norway (July 8, 2009)

[112] LTS International, "Capability and cost assessment of the major forest nations to measure and monitor their forest carbon" prepared for Office of Climate Change (7 April, 2008)

Table 10: Strengths and limitations in estimation of terrestrial carbon from space and air[113]

Potential strengths	• May provide relatively speedy and consistent access to information required to map extent of biomass (carbon) stock and changes over large areas; • Biomass distribution can be represented spatially (not just as local or regional averages); • Provide change detection on a routine basis and in inaccessible regions • Potential to map at scale (national or regional); • Data are captured on lands not included in inventories (remote forests, other wooded lands, lands with wood encroachment) • Shows the fraction of forests that are growing, and how that varies regionally (provides quantitative information on rates of disturbance); • May be used to improve data collection (sampling) • Globally accessible data, large user communities and transparent processing methodologies allow for internationally consistent monitoring systems
Potential limitations	• Continuity of sensor types across a suite of spectral, temporal, and spatial scales are not assured (e.g. for Landsat). • No direct, operational assessment of soil carbon stocks. Likely to miss other terrestrial pools (fallen dead biomass, below ground biomass, soil carbon, wood products). • Cloud cover over major regions of the tropics can cause major constraint on use of optical sensors, alone. • Unlikely to be precise enough to see "cryptic deforestation" (i.e. biomass removal which does not affect canopy closure). Changes at larger scales are more readily observed. Positive or negative carbon density changes (and therefore the emissions factor) may not be fully captured. Depending on definitions, it is more suitable for measuring deforestation than degradation. [114] • Assumes that the independent variable (typically the field measurement) is accurate[115]. Having information on land use, land cover, and changes does not necessarily mean you have accurate information on biomass and carbon, or on emissions and sequestrations; • Saturation of the sensors may occur in some areas where LAI>5, leading to inaccurate results. [116] This may be overcome using lidar. Low saturation may not be an issue where remote sensing is required to measure or monitor less dense areas (e.g. degradation).[117] Many of the newer sensor types are still in the research and testing phase. • Interpretation techniques (e.g. using algorithms) can be complex and may require refinement – for example there is a need to develop new methods to link biophysical variables (such as LAI) to spectral reflectance to support spatially distributed carbon sequestration models[118]

[113] Adapted from: Sánchez-Azofeifa, G.A., Castro-Esau, K.L., Kurz, W.A., and Joyce, A. "Monitoring carbon stocks in the tropics and the remote sensing operational limitations: from local to regional projects." Ecological Applications, 19(2), (2009), 480-494.

[114] Laurance, W.F., Laurance, S.G., Ferreira, L.V., Rankin de-Merona, J.M., Gascon, C., and Lovejoy, T. "Biomass Collapse in Amazonian Forest Fragments." Science, 7 (1997), 1117-1118.

[115] Sánchez-Azofeifa, G.A., Castro-Esau, K.L., Kurz, W.A., and Joyce, A. "Monitoring carbon stocks in the tropics and the remote sensing operational limitations: from local to regional projects." Ecological Applications, 19(2), (2009), 480-494.

[116] Ibid.

[117] Pers. Comm. Holly Gibbs, SAGE, University of Wisconsin (25 March 2009)

[118] Sánchez-Azofeifa, G.A., Castro-Esau, K.L., Kurz, W.A., and Joyce, A. "Monitoring carbon stocks in the tropics and the remote sensing operational limitations: from local to regional projects." Ecological Applications, 19(2), (2009), 480-494.

2.3 Models

Typical inputs for models include information related to carbon stock estimates and activity data, for example: Current and historic natural disturbance, management, land use change, climate, soil properties, growth rates, decomposition rates, biomass pools (above and below ground estimates) and estimates of variability and error.

Consistent with the IPCC guidance, inputs can either be defaults (Tier 1), or site-specific information (Tier 3), or a combination of the two (Tier 2). Moving from Tier 1 to higher tiers has cost implications and quality implications, as demonstrated by Figure 7.

A wide range of models exist; in fact, all extrapolation of measurement data requires some type of model. Models can be empirical, for example based on existing inventory data (e.g., FORCARB)[119] or yield curves (e.g. CO2FIX), or mathematical representations of processes that drive carbon losses and gains (e.g. CENTURY).[120] Fundamentally, these all rely on the quality of inputs in the form of either remote sensing information or field methods. This section provides some examples of currently used models (see Table 11, below), and describes experiences with, and application to, estimating carbon. Although allometric equations are essentially simple types of models, they are covered in Section 2.1 above.

Table 11: Examples of models

Type	Purpose	Data sources	Examples
Commercial harvest tool	Stand level yield prediction	Volume, age, forest inventory, disturbance	Woodstock, SFMM, FSSIM
Stand or landscape level carbon accounting	Stand-level estimation of carbon stock change between inventories	Based on forest inventory	FORCARB, CBM-CFS3, CO2Fix
Models plant and soil components	Estimate change in (soil) carbon stocks in agricultural and other soils	Based on soil base map, management, weather data, etc. Allocates carbon to pools.	Century, Biome-BGC
Remote sensing models	Interpretation of remote sensing information[121]	Remotely sensed data, field data	EOSD (See Appendix IV)

[119] Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., and Apps, M.J. "CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards." Ecological Modelling, 220 (2009), 480-504.

[120] Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., and Apps, M.J. "CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards." Ecological Modelling, 220 (2009), 480-504.

[121] GOFC-Gold, 2008. Reducing Greenhouse Gas Emissions from Deforestation and Degradation in Developing Countries: A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting, GOFC-Gold Report version COP 13-2, (GOFC-Gold Project Office, Natural Resources Canada, Alberta, Canada). Available at: http://www.gofc-gold.uni-jena.de/redd/index.php

As with the other methods described in this report, models tend to be synergistic, for example two commonly used soil carbon models, RothC and Biota, are complementary.[122] Additionally, models that focus on different carbon pools can be combined in order to provide an estimate of carbon transfer between pools. However, some models may themselves incorporate other models that focus on specific carbon pools better than others. It is also possible to combine global models (e.g. NASA models on global NPP or BIOME BGC) with local models so that global models feed results into more localized models. Improvements to existing models and new models are continuously being developed and combined to better meet information requirements.

The quality of outputs of models depends on the quality of inputs and the international system design to reduce emissions and enhance sequestration, including ensuring that a quality independent variable is used,[123] for example, by using geographically specific inputs.[124] Many well-accepted models exist, including the Canadian system described in Appendix V, and others such as the Australian NCAS and NCAT system.[125] Models that integrate information from a variety of information sources are also used in non-Annex I contexts, for example in Brazil, Mexico and Indonesia[126].

[122] Falloon, P., and Smith, P. "Adding Vegetation Carbon to the RothC Soil Carbon Model." Section 5 of a report to DEFRA from the Rothamsted Research Centre, U.K. (2003). *Available from Dr. Pete Smith upon request.*

[123] Sánchez-Azofeifa, G.A., Castro-Esau, K.L., Kurz, W.A., and Joyce, A. "Monitoring carbon stocks in the tropics and the remote sensing operational limitations: from local to regional projects." Ecological Applications, 19(2), (2009), 480-494.

[124] Houghton, R.A. "Aboveground Forest Biomass and the Global Carbon Balance." Global Change Biology, 11 (2005), 945-958. Available at: http://www.whrc.org/resources/published_literature/pdf/HoughtonGCB.05.pdf

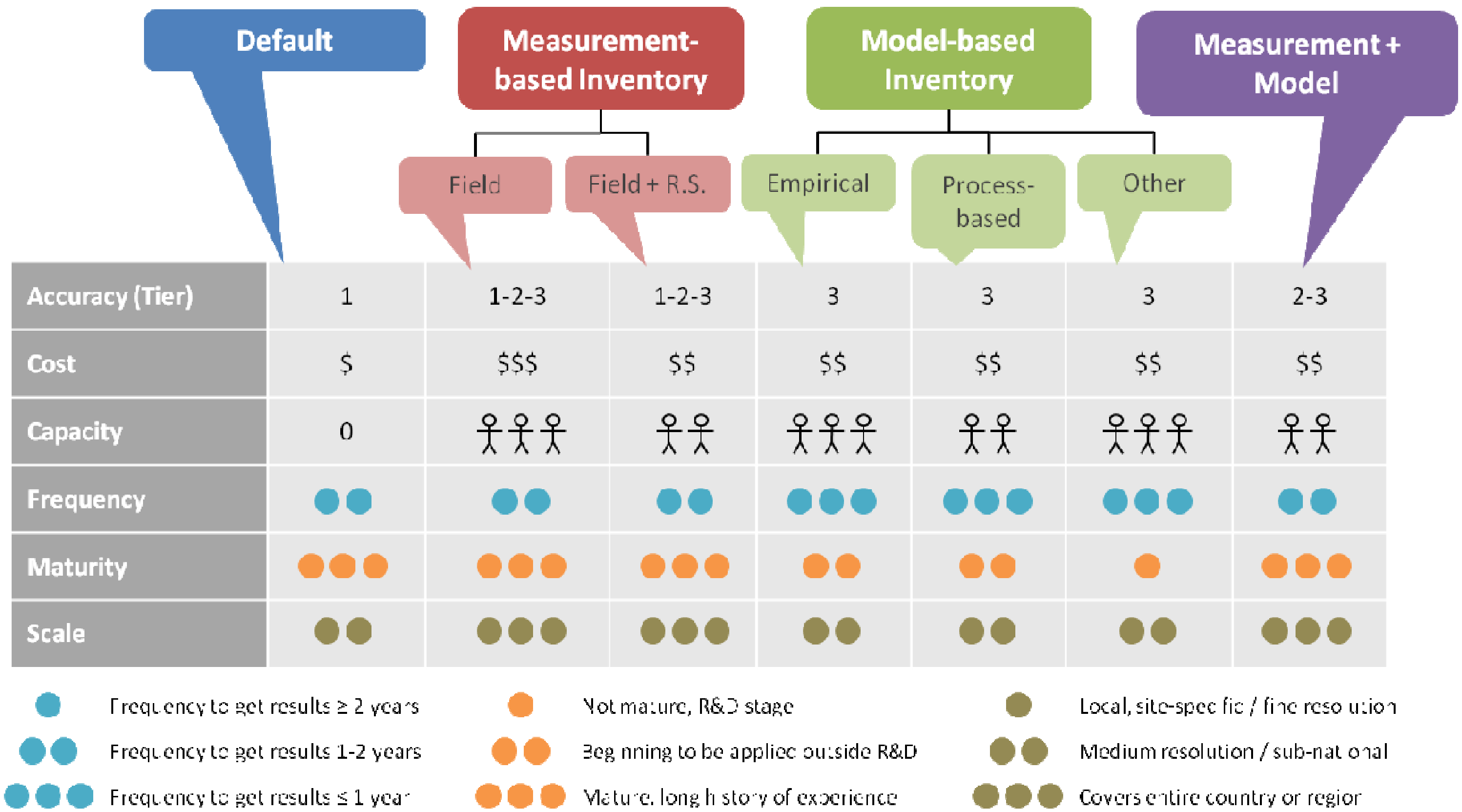
[125] For more information on the Australian National Carbon Accounting System (NCAS) and the National Carbon Accounting Tool (NCAT), see: http://www.climatechange.gov.au/ncas/about.html

[126] For an overview of some of the current models and information sources used please refer to the June 2009 SBSTA paper: "Information on experiences and views on needs for technical and institutional capacity-building and cooperation", Submissions from Parties. Available from http://unfccc.int/resource/docs/2009/sbsta/eng/misc02.pdf and from http://unfccc.int/resource/docs/2009/sbsta/eng/misc02a01.pdf (Brazil, Mexico, Nepal)

2.4 Evaluation Matrix

The figure below summarizes the capabilities of individual categories of measurement and estimation methods described in Chapter 3.

Figure 6: Evaluation Matrix



3 ASSESSMENT OF MEASUREMENT AND MONITORING OPTIONS AND SYSTEM DESIGN

In order to evaluate the strengths and weaknesses of different tools and methods for biomass measurement and monitoring, current proposals for including terrestrial carbon into an international climate change agreement are briefly considered in the following sub-section ("System Design"). The implications of these different design options are discussed and examples provided about how a country might develop such a system.

3.1 System design issues

The main system design issues currently under discussion relate to three broad and inter-related themes:

- *Scope and scale: what* is to be estimated, i.e. deforestation, degradation or all terrestrial carbon pools in all land use systems, scale (national, project-level), and what, if any, benchmark or emission level this is compared to (net-net or gross-net accounting);
- *Measurement and estimation: how* it is estimated, reported and accounted for, including change in stock vs. gain-loss methods;
- *Funding and liability: who* is responsible, and who pays, i.e. private, public, or a combination of public and private funding, liability for measuring, monitoring and reporting carbon stocks and terrestrial emissions

This Chapter first describes some of the primary design considerations and options for a complete system to reduce terrestrial emissions and enhance removals (Table 12). Existing design parameters are then summarised, and likely system design options considered. Finally, the existing methods described in the previous Chapter are evaluated in the context the system design options, and two examples provided for how a country might use a mix of complementary methods to develop a measurement and monitoring scheme that could fit within the evolving system.

The table below indicates some of the general system design considerations, and indicates options and examples. System design considerations have been discussed in detail in other papers, for example the Options Assessment Report produced for the Government of Norway.[127] Once the principles of the system have been decided, existing information and data gaps can be thoroughly evaluated, and planning for how to collect missing elements can take place.

[127] Meridian Institute. 2009. "Reducing Emissions from Deforesation and Degradation (REDD): An Options Assessment Report". Prepared for the Government of Norway, by Arild Angelsen, Sandra Brown, Cyril Loisel, Leo Peskett, Charlotte Streck, and Daniel Zarin. Available at www.REDD-OAR.org

Table 12: Some system design considerations

	Considerations	Options	Examples
International system design	Land use categories included (scope)	Forests, croplands, grasslands, wetlands, settlements, other areas	RED, REDD, REDD+, AFOLU
	Participation requirements	Tiers 1, 2 or 3 reporting ability for included land use categories Reporting requirements	Minimum ability to report national forest cover at Tier 2 Requirement to report annually or periodically against a reference emission level
	Responsibility (funding & liability)	National, Nested or sub-national approaches	National REL and leakage[128] monitoring but some project-level activity
National implementation	Existing information gathering frameworks	Rely on existing systems, and / or Purchase historical RS images	National Forest Inventory information Purchase of MODIS images
	Availability of default values, equations and models	Rely on existing allometric equations Develop new equations or models Adapt existing models	Adaptation of Australian carbon model to suit Indonesian conditions
	Country characteristics	Adapt measurement methods to local conditions (environmental, economic, financial, social, institutional)	Higher dependence on field measurement methods in countries with low labour cost
	Measurement and estimation	Stock-difference or gain-loss	Availability of good inventory data – may favour stock-difference approach

3.1.1 Land use categories included

National systems to estimate terrestrial carbon will reflect the outcome of the UNFCCC negotiations on scope. This is likely to initially cover existing natural forests and enhancement of forest carbon stock (REDD+), but then expand to include other land uses (AFOLU). In forests, ABG is typically the largest pool that is most readily quantifiable, and in most cases, the one that is most directly threatened. In peatlands and wetlands SOM may be the largest pool, but may be more difficult to quantify. Therefore, as scope is expanded, national measurement and monitoring systems will need to incorporate or adapt methods so that they more fully and efficiently capture added land use categories, and the significant carbon pools within them. While measurement methods exist for all

[128] Leakage is defined here as emissions ("negative leakage") or removals ("positive leakage") occurring outside the national or sub-national boundary as a result of the terrestrial-carbon activities.

major carbon pools, they are at varying levels of maturity for efficient application in a national-level assessment

Common considerations for the inclusion of a broader set of land use classes at the national level are:

- Local management practices, including land use change drivers;
- The boundaries of the national forest definition;
- Land use class fragmentation and spatial heterogeneity;
- Local climatic variability (e.g. When measurement can take place and timing of crops);
- Local stakeholders and land tenure: it is useful to know who is involved (formally or informally) with the management of the land, both in terms of initial data collection (measurement) and monitoring.

The table below describes scope options and examples in the current discussions.

Table 13: Potential inclusions in terrestrial carbon accounting systems

	What is covered?	Measurement and estimation considerations
RED	Existing areas that classify as forests given the national forest definition and the UN default definition	Quality of existing forest data Availability of historical images (e.g. Landsat) Availability of appropriate allometric equations & models Access to medium-high resolution RS imagery
REDD	Inclusion of forest and degraded forests	Similar to above, but: ▪ More intensive field measurements ▪ Higher-resolution RS imagery
REDD+	As above, but includes conservation of forest carbon stocks, sustainable forest management and enhancement of forest carbon stocks	Similar to above but also emphasis on quality information collection procedures on forest management
AFOLU	Full terrestrial carbon accounting	As above but also: ▪ Application of more refined land use classification system ▪ More comprehensive models ▪ Historical information on non-forest land use categories (carbon density and area change) ▪ Additional land management information (e.g. fertilizer application)

3.1.2 National and sub-national

National and project-level activities tend to have slightly different data requirements. Commonly, project-level activities are focussed on smaller areas and emphasize finer geographic and temporal scales of measurement. National-level activities are focussed on coarser measurement scales but may be more comprehensive for major land use categories. In addition, project-level activities will have more stringent measurement and monitoring requirements. They are also likely to require more onerous estimates of leakage effects, whereas national-level approaches require assessment of intra-national leakage (i.e. that reducing deforestation will not lead to more degradation). Project and national-level activities may also make use of different measurement methods. For example, project-level monitoring might rely more heavily on field measurements to achieve greater accuracy and precision, while national-level monitoring may rely to a greater extent on remote sensing that can provide extensive coverage and detect changes in land uses.

In its current form, the Kyoto Protocol specifies reporting of terrestrial emissions and sequestration in two ways: through national-level reporting and through project-level activities – i.e. the flexible mechanisms (CDM and JI). There are significant differences between how emissions and removals are treated under national-level reporting versus the project-level flexible mechanisms, in terms of extent and timing of coverage. National-level reporting requires annual assessment and reporting of some sources, but in some cases does not catalyze much independent scrutiny. Project-level flexible mechanisms require more detailed reporting in a smaller area, following a strict process with a high degree of independent scrutiny, but, only requires assessment (and potential financial reward) once every five years. The key differences are summarised in Table 1 in Chapter 1.

A mechanism for RED, REDD, REDD+ or AFOLU could be implemented as either a national-level system or a project-level flexible mechanism-based system – or a combination of the two. One example of how projects might be integrated into national-level system over time is the Track 1 and Track 2 categories under the Joint Implementation[129] flexible mechanism, which puts in place more stringent criteria (double verification) for projects developed in countries without adequate national reporting systems.

3.1.3 Measurement and estimation premise

In Section 1.2, the two methods for estimating change in carbon stocks over time were described: the stock-difference and the gain-loss approaches. Some of the implications for the use of these methods are described in the table below. The IPCC provides detailed decision trees for how land use categories and pools should be estimated at various tiers, using these methods.[130] Both methods require an understanding of national carbon stock changes and land use area changes over time.

---

[129] See http://unfccc.int/kyoto_protocol/mechanisms/joint_implementation/items/1674.php

[130] See 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use

Table 14: Differences between the IPCC's two measurement frameworks

	Inputs	Examples	Consequences
Stock-Difference	Carbon stock estimates for relevant land use classes and pools at two different points in time. Area estimates for relevant land use classes and sub-classes at two different points in time.	Repeated inventory measurements over time	More resources required to carry out estimates over time Depending on time period, may show more variability Tier 2 or 3
Gain-loss	Annual incremental growth and loss in biomass or carbon for each land use category / sub-category, plus time that it is included in that category.	Process based models	Smoother inter-annual variability May be Tier 1, 2 or 3

3.1.4 Costs of measurement and estimation

Any measurement and monitoring system for RED, REDD, REDD+ or AFOLU will have start-up and on-going costs, including costs to put in place appropriate institutions and frameworks ("readiness"). Costs depend on the particulars of system design, the country characteristics and the quality of pre-existing data and infrastructure.[131] Assessments of how much it would cost to put in place monitoring, reporting and verification systems for RED and REDD have been carried out by LTS International,[132] among others, which found considerable heterogeneity among countries with regard to the level of funding required to implement national-scale accounting for RED and REDD. Both references provided below (LTS 2008 and UNFCCC 2009) state that there is significant potential to reduce costs through stronger regional cooperation.

Costs cited in LTS (2008) provide the following example ranges[133]:

- Estimated costs for establishing a monitoring system: £250,000 – £1m based on information from Brazil and India (2007 data)
- Estimated costs for a national carbon inventory: £0.025 - £0.30 per hectare (2000 data)

---

[131] These cost factors are described in detail in: UNFCCC, 2009. Technical Paper: "Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks". Reference: FCCC/TP/2009/1. 31 May 2009. Available from: http://unfccc.int/resource/docs/2009/tp/01.pdf

[132] LTS International (2008). "Capability and cost assessment of the major forest nations to measure and monitor their forest carbon, for Office of Climate Change." UK.

[133] All examples are from LTS International (2008), p. 9

- National forest survey (Cameroon), excluding remote sensing: £500,000 (2006 data)
- Establishing a national REDD monitoring program: £100,000 to £475,000 p.a. for ground sampling, £200,000 to £400,000 p.a. for analysis of remote sensing data and £60,000 to £120,000 p.a. for data costs, resulting in total costs of between £360,000 to £995,000 p.a. (2008 data).

Additional information on costs was also provided in a UNFCCC Technical Paper:

Table 15: First order country estimates based on the Readiness Plan Idea Notes (R-PINs), discussions with developing countries undertaking activities to reduce emissions from deforestation and forest degradation and independent estimates (in thousands of US$)[134]

Major components of readiness	Estimate [a]	Country [b]	R-PIN [c]	Average [d]
REDD management	440–490	130–430	550–1 115	525
Develop REDD Strategy	500	200–410	400–690	450
Consultations	420	380–440	350–182	365
Environment and social impacts assessments	50	50	50	50
REDD implementation framework	250–500	300–350	150–500	341
Develop reference scenario	500	200–400	300–1 200	516
Design MRV[in full please] system	1 000–1 300	1 000–1 560	250–940	1 008
TOTAL (without annual measurement, reporting and verification costs)	**3 160-3 760**	**2 2640–3 640**	**2 050–4 627**	**3 255**

[a] Bottom up estimates by the World Bank based on the tasks that need to be performed.
[b] Estimates by the World Bank based on staff missions to several tropical developing countries and R-PINs submitted by countries.
[c] Estimates submitted in the R-PINs, including one or two countries of different tropical regions.
[d] The average estimate reflects cost estimates for smaller/medium-sized countries.
Source: World Bank Forest Carbon Partnership Facility presentation at the second Participants Committee, Gamboa 2009. Data up to October 2008.

Information on project-level activity costs are not readily available as many RED, REDD, REDD+ or AFOLU-type projects are not mature and many are developed by private companies that are typically unwilling to disclose such confidential information. Anecdotal evidence suggests that, for private RED or REDD projects; the largest measurement and estimation costs are often purchase and interpretation of remote sensing images. For CDM A/R projects, anecdotal evidence suggests that the largest measurement and estimation costs are associated with labour which is greatest for approaches that rely more heavily on field measurements. Monitoring of carbon pools or land use categories that are difficult to estimate using remote sensing will also rely more heavily on field measurements and this will be reflected in higher costs.

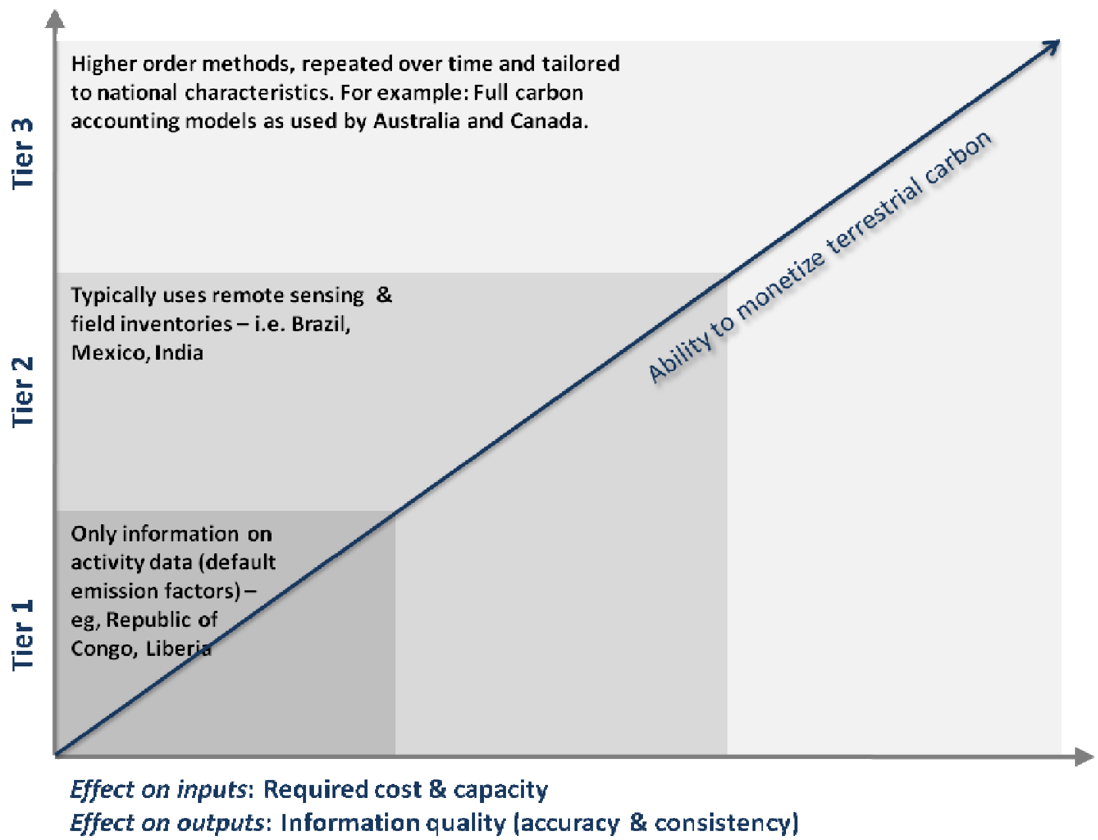
It would be particularly interesting to understand measurement and monitoring costs and accuracy tradeoffs associated with different system design options (scope and scale). Another interesting question is the interaction between reporting tier costs and potential rewards, both for national-

---

[134] UNFCCC, "Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks". Technical Paper FCCC/TP/2009/1. 31 May 2009.

level and project-level activities. An overview of the trade-offs between various approaches and an example is provided in Figure 7 below.

Figure 7: Overview and examples of the effects of achieving higher quality estimates



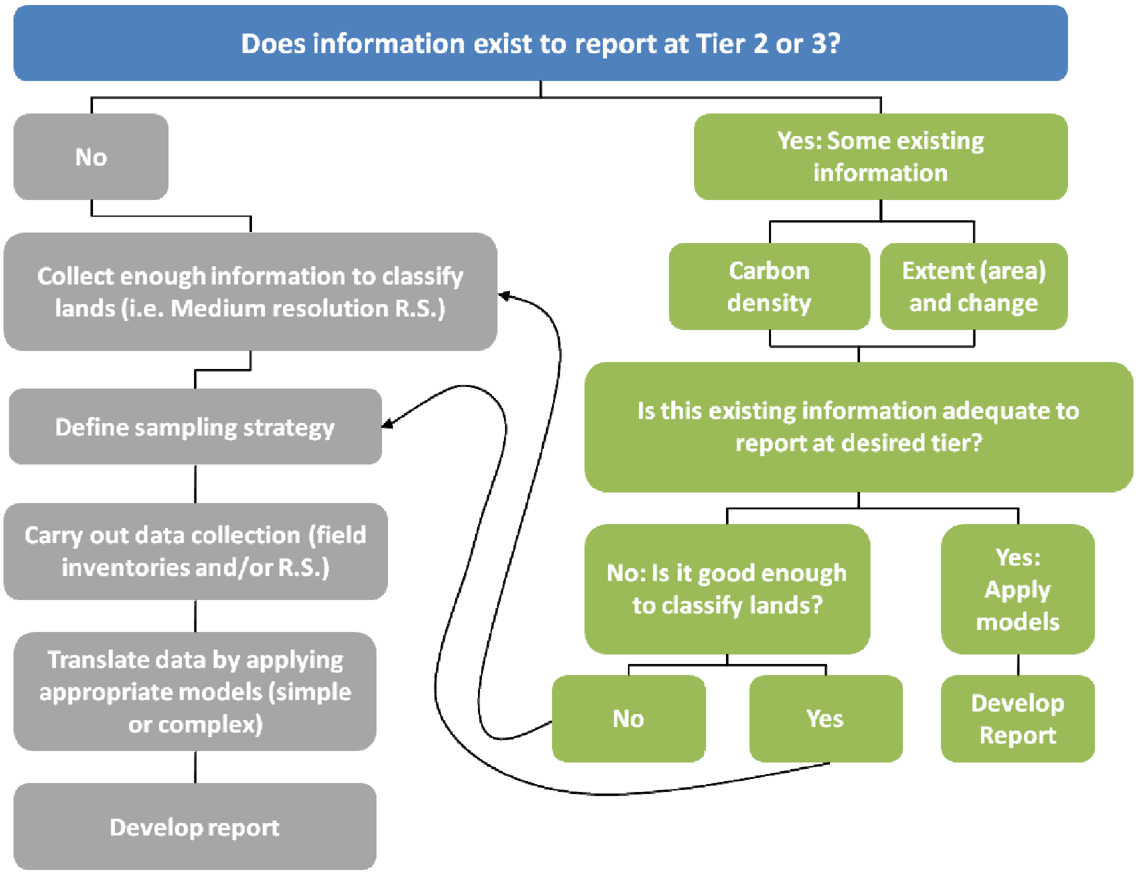
3.2 Putting a system together: general guidelines and examples

It is likely that incentives for including terrestrial carbon will favour countries that provide Tier 2 or 3 data for the most significant sources and sinks. The basic information requirements are therefore:

- Carbon density measurements for major land use categories – this requires a combination of direct field measurements (to estimate biomass) coupled with conversion equations and / or models
- Estimation of the areal extent of significant land use categories, typically using remote sensing combined with field measurements
- Monitoring of changes to carbon density within major land use categories; this requires field estimates and allometric equations and / or models and / or ground-tested remote sensing that provide information pertaining to carbon density
- Monitoring of land use change within and between various classes, typically requiring remote sensing.

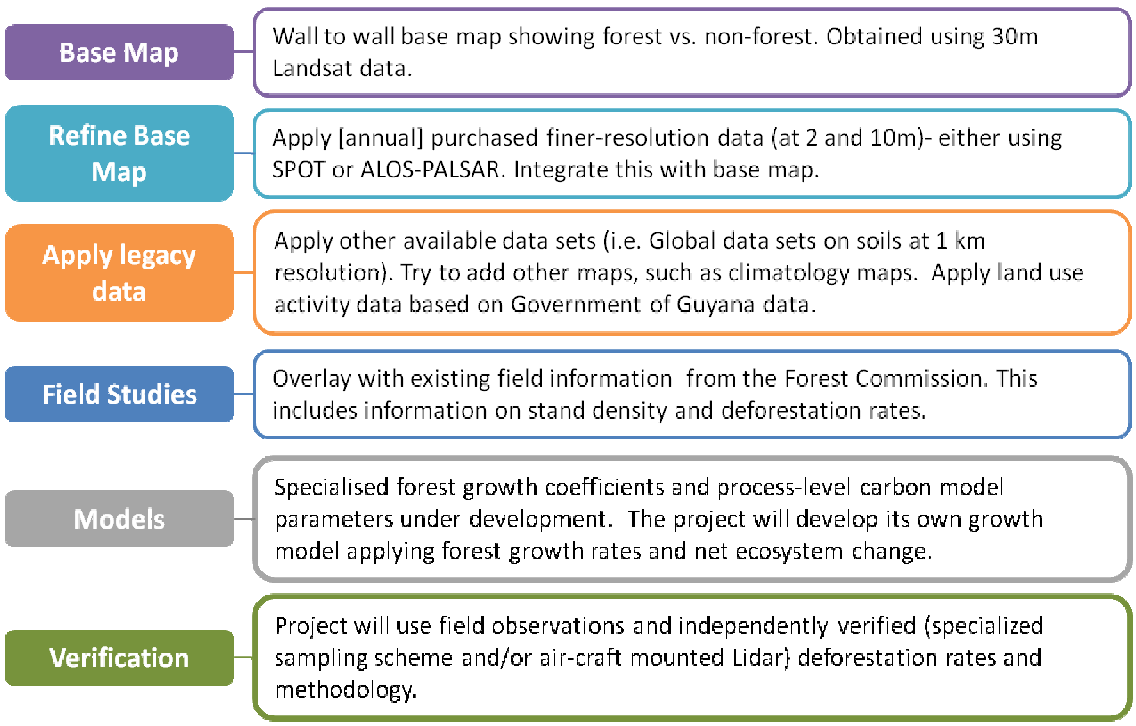
A highly simplified process diagram of how a country that has little or no existing information might begin to develop this is provided below (Figure 8). This is complemented by two further examples below, one from Guyana and another from Papua New Guinea (Figures 9 and 10).

Figure 8: Simplified overview of decision steps required to produce Tier 2 or 3 reports



The figure below is an example of how information from remote sensing, field methods and models can be used together to develop a forest map.

Figure 9: Mapping Guyana's Forest Cover, a Collaboration between the Government of Guyana and the Clinton Climate Initiative

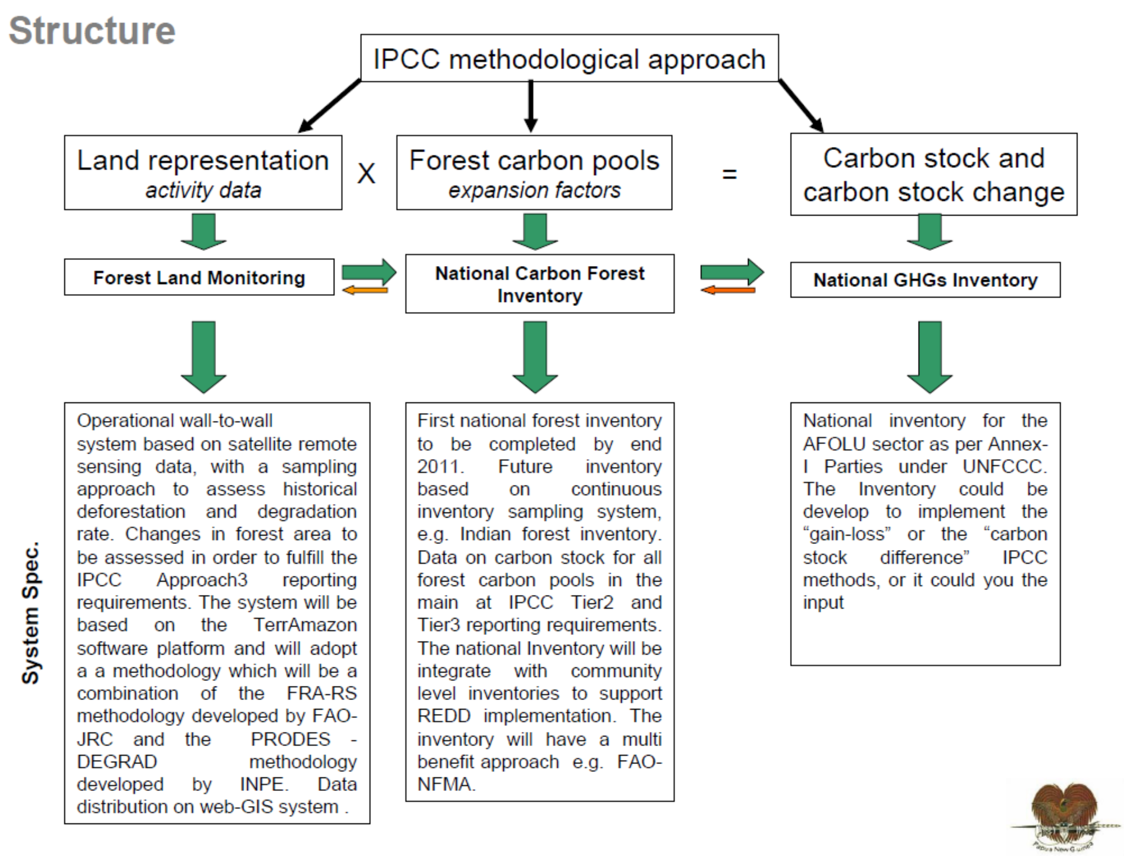


Program is being developed through joint action with international partners and sharing of resources including acquisition of remote sensing data.

Reference: Pers. Comm. Dennis Ojima, The Heinz Center (16 March, 2009)

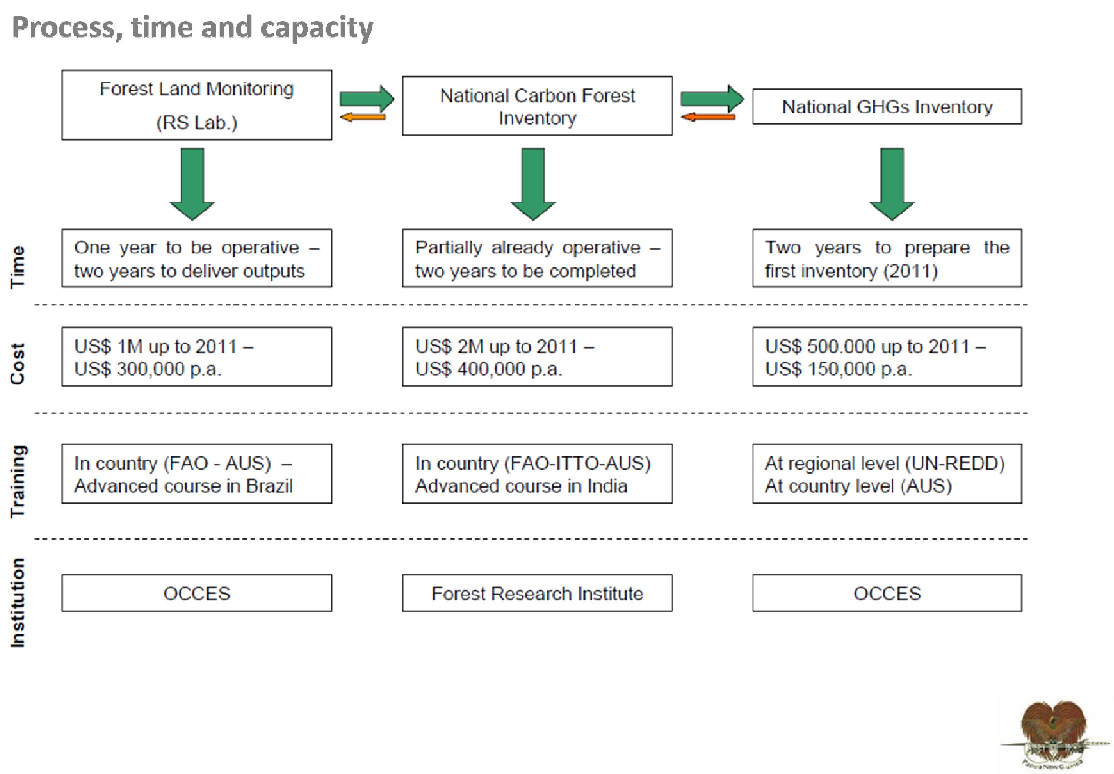
The following example presents the Papua New Guinean National System to monitor and report GHGs emissions from forest lands.

Figure 10a: Structural overview and implications for implementing Tier 2/3 national REDD approaches in Papua New Guinea[135]



[135] Presentation by Joe Pokana (Director, Climate Change, Office of Climate Change and Environment Sustainability): "Towards REDD: the Papua New Guinea National System to monitor and report GHGs emission from forest land". Presented at UN-REDD II Policy Board Meeting, Switzerland, 14-15 June 2009. Available at: http://www.un-redd.org/Portals/15/documents/events/Montreux/presentations/UN-REDD_PB2_PNG_MRV_Presentation.pdf

Figure 10b: Structural overview and implications for implementing Tier 2/3 national REDD approaches in Papua New Guinea[136]



[136] Presentation by Joe Pokana (Director, Climate Change, Office of Climate Change and Environment Sustainability): "Towards REDD: the Papua New Guinea National System to monitor and report GHGs emission from forest land". Presented at UN-REDD II Policy Board Meeting, Switzerland, 14-15 June 2009. Available at: http://www.un-redd.org/Portals/15/documents/events/Montreux/presentations/UN-REDD_PB2_PNG_MRV_Presentation.pdf

4 CONCLUSIONS

4.1 Summary

A variety of appropriate and tested measurement and monitoring tools and methods exist for carbon stocks and changes in forests, particularly for the above-ground biomass pool. A range of countries have experience using various combinations of field measurements, remote sensing and models. Although tested and applied in a few countries, more advanced combinations of these methods have yet to be as widely implemented for measuring and monitoring emissions and sequestrations from non-forest land use classes and non-ABG carbon pools. However, given the increasing interest of nations to establish an international incentive scheme that rewards sustainable land use management, this is rapidly changing. Some research suggests that there may already be significant economies of scale in including forest degradation[137] in an international agreement, and this may also extend to the inclusion of forest conservation and enhancement (REDD+) activities in national systems. The quality of such measurement and monitoring systems and the speed at which they are implemented will be a reflection of potential tangible and intangible rewards to stakeholders.

The ease with which a high quality (Tier 2 or 3) measurement and monitoring system for ABG biomass can be implemented relies on the quality and availability of existing data, including appropriate allometric equations and models. Relevant existing information includes field measurements (e.g. National Forest Inventories) and remotely sensed images. Going forward, countries will need to develop nationally appropriate frameworks to monitor carbon density changes as well as land use changes over the national landscape. This is valid both for the stock-difference and gain-loss methods, although the specific combinations of methods are likely to differ depending on measurement and estimation.

It must be stressed that different methods and types of information are complementary, and the optimal combination depends on national (or sub-national) characteristics. The ability to take advantage of existing methods relates fundamentally to capacity – existing national capacity will therefore be reflected in the combination of methods and the quality of national reporting. Finally, terrestrial carbon is a critical factor in the global carbon cycle. It is therefore imperative that proper incentives be created that would encourage the use of appropriate and high-quality measurement and monitoring methods and would maximise terrestrial carbon sequestration and minimise terrestrial carbon emissions.

---

[137] LTS International (2008). "Capability and cost assessment of the major forest nations to measure and monitor their forest carbon, for Office of Climate Change." UK.

4.2 Implications and recommendations

In the near term, most countries would be able to implement some form of national measurement and monitoring system for the forest land use class (including new sequestration), even though these will probably range in quality from Tier 1 to 3. There is currently considerable variety in the capacity to report the full range of terrestrial carbon pools, even within Annex I countries. Better coordination and sharing of information and technology is necessary to support non-Annex I countries in adopting national-level terrestrial carbon reporting commitments. The national capacity of non-Annex I countries to report deforestation, and degradation, at higher tiers of reporting quality is being encouraged and developed with assistance from multilateral agencies and a variety of other institutions (including the World Bank Forest Carbon Partnership Facility, UN-REDD, Conservation International, Government of Norway, etc.). This support is necessary, and would need to be coordinated and result in the development of sustainable long-term terrestrial carbon inventory, reporting and accounting frameworks at the national level.

Many of the current issues constraining the debate are not related to technical measurement and monitoring issues, but rather to more political issues such as permanence, additionality and leakage. Credible ways to deal with these issues must be agreed, and in a manner that incentivises rapid, real and quality participation, in order to prevent a repeat of past failures to spur better management of terrestrial carbon under the Kyoto Protocol.

The scale and quality of measurement and monitoring systems will also expand if it becomes easier and cheaper to access and interpret remote sensing images and if high-quality national initiatives to map land use and monitor carbon stocks (e.g. through models) become more widespread. It is therefore recommended that the continuity of key historical remote sensing images be guaranteed and that reasonable cost and accessibility (e.g. in terms of interpretation) of such images be prioritised. Better access to common data sources and the implementation of standardized classification and interpretation techniques may also facilitate more comparable terrestrial carbon reports.

An agreed incentive scheme would facilitate deployment of additional resources to develop quality measurement and monitoring systems. This incentive scheme would be flexible and dynamic, and result in terrestrial carbon information that is comparable and yield results that are spatially and temporally consistent. Specifically, this could be expedited by:

- Agreeing to a set of international, practicable "best practices", which build on IPCC guidance, and facilitate the development of more standardised measurement and monitoring methods. These would be dynamic and assessed and updated by a centralised body. Clear support would be needed for the implementation of these practices.
- Increasing the clarity and consistency of international definitions related to terrestrial carbon and maps, including land cover classes and soil maps (e.g. adoption of a common standardised land cover classification system).
- Ensuring the continuity of widely used coarse and medium-resolution remote sensing data and free access to the most commonly used types of remote sensing.
- Sharing and adapting existing models, and making adaptable versions of these available and easily accessible.

- Building a common data archive of carbon studies and remotely sensing images and data and training local staff in data interpretation. This would be additional to increased information sharing and coordination of terrestrial carbon measurement and monitoring experience, including information-sharing on pilot projects (including in the voluntary market), costs and data resources.
- Investing in the expansion and sharing of credible default-value databases and databases for conversion (allometric) equations, such as the IPCC's Emissions Factor Database (EFDB).
- Examining, enabling, and incentivising the use of measurement and monitoring systems for terrestrial carbon to collect other information, e.g. related to biodiversity or socioeconomic information.

APPENDIX I: KEY TERMS AND DEFINITIONS

Term	Definition	Reference	Issues
Above-ground biomass pool	"All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds and foliage"	IPCC 2006	
Below-ground biomass pool	"All biomass of live roots. Fine roots of less than 2 mm diameter (the suggested minimum) are often excluded because these often cannot be distinguished empirically from soil organic matter."	IPCC 2006	
Dead wood pool	"All non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Deadwood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter."	IPCC 2006	
Deforestation	"the direct human-induced conversion of forested land to non-forested land."	Decision 11/CP.7	- Definition of deforestation depends on the national forest definition (reduction in crown cover to below the threshold definition) - Baseline year from which deforestation is measured - Implies a permanent event – the permanence of deforestation depends on the time period over which it is measured - Differentiating between human and natural deforestation events may be problematic

Term	Definition	Reference	Issues
Degradation	"A direct human-induced, long term loss (persisting for X years or more) or at least Y% of forest carbon stocks [and forest values] since time T and not qualifying as deforestation."	IPCC Special Report on "Definitions and Methodological Options to Inventory Emissions from Direct Human-Induced Degradation of Forests and Degradation of Other Vegetation Types"	- Affected by the definition of forest and deforestation - Degradation may, in fact be deforestation - Human vs. Natural - Significance depends on scale (and type)
Forest	"...a minimum area of land of 0.05 to 1.0 ha with tree crown cover (or equivalent stocking level) of more than 10 to 30% with trees with the potential to reach a minimum height of 2 to 5 meters at maturity in situ. A forest may consist either of closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10-30% or tree height of 2-5m are included under forest, as are areas are normally forming part of the forest area which are temporarily under stocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest..."	UNFCCC Marrakesh Accords, UNFCCC COP 2002a p. 58	- Nation specific (not consistent) - Excludes variability in ecological conditions - Year since forest is classified as such (for A/R this is 1990) - Use of different definitions affects observation requirements[138]
Harvested Wood Products pool	"HWP includes all wood material (including bark) that leaves harvest sites."[139]	IPCC 2006	

[138] GOFC-Gold: use of different definitions affects the technical earth observation requirements and could influence cost, availability of data, abilities to integrate and compare data through time.

[139] http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_12_Ch12_HWP.pdf

Term	Definition	Reference	Issues
Litter pool	"All non-living biomass with a size greater than the limit for soil organic matter (the suggested minimum is 2 mm) and less than the minimum diameter chosen for deadwood (for example 10 cm) lying dead and in various states of decomposition above or within the mineral organic soil. This includes the litter layer as usually defined in soil typologies. Live fine roots above the mineral or organic soil (of less than the suggested minimum for below-ground biomass) are included whenever they cannot be empirically distinguished from the litter."	IPCC 2006	
Measurement	"Process of data collection over time, providing basic datasets, including associated accuracy and precision, for the range of relevant variables. Possible data sources are field measurements, field observations, detection through remote sensing and interviews."	UN-REDD Draft Discussion Paper: Measurement, Assessment, Reporting and Verification (MARV): Issues and Options for REDD.[140]	- Field measurements (in-situ): destructive and non-destructive - Non in-situ measurements: information collected using air or space-borne sensors
Reference Emissions Level	"The reference emissions level (REL) is the amount of gross emissions from a geographical area estimated within a reference time period."[141]	REDD-UNFCC Expert Meeting 2009	
Reference Level	"The reference level (RL) is the amount of net/gross emissions and removals from a geographical area estimated within a reference time period."[142]	REDD-UNFCC Expert Meeting 2009	

140 Draft Paper developed by FAO to inform the UN-REDD process. Draft paper produced March 2009

141 "Methodological issues relating to Reference Emission Levels and Reference Levels", 23-24 March 2009, Bonn, Germany

142 "Methodological issues relating to Reference Emission Levels and Reference Levels", 23-24 March 2009, Bonn, Germany

Term	Definition	Reference	Issues
Reporting	"The process of formal reporting of assessment results to the UNFCCC, according to predetermined formats and according to established standards, especially the IPCC Guidelines and GPG. It builds on the principles of transparency, consistency, comparability, completeness and accuracy."	UN-REDD Draft Discussion Paper: Measurement, Assessment, Reporting and Verification (MARV): Issues and Options for REDD.[143]	- National reporting - Stocks vs. flows - Reporting for carbon credit projects
Soil Organic Matter pool	"Organic carbon in mineral soils to a specified depth chosen and applied consistently through a time series. Live and dead fine roots within the soil (of less than the suggested minimum for below-ground biomass) are included whenever they cannot be empirically distinguished from the soil organic matter."	IPCC 2006	
Verification	"The process of formal verification of reports, for example the established approach to verify national communications and national inventory reports to the UNFCCC."	UN-REDD Draft Discussion Paper: Measurement, Assessment, Reporting and Verification (MARV): Issues and Options for REDD.[144]	- Must be less capacity consuming than initial measurement and assessment

[143] Draft Paper developed by FAO to inform the UN-REDD process. Draft paper produced March 2009

[144] Draft Paper developed by FAO to inform the UN-REDD process. Draft paper produced March 2009

APPENDIX II: EXAMPLES OF NATIONAL ASSESSMENTS

FAO National Assessments

FAO provides support to national forest monitoring and assessment (NFMAs). The purpose of this is to improve national forest monitoring at the national level, and between countries. FAO is adapting the NFMAs to collect information on carbon stocks and biomass, including at the sub-national level. By supporting countries to develop better national forest inventories, the quality of publicly available information will improve. Twenty two tropical forest countries have been supported by NFMA, including Brazil, Zambia and Viet Nam.

The Forest Resources Assessment (FRA) is primarily a compilation of national information using country reports and remote sensing assessments at sampling sites. The Report is issued by FAO once every five years, taking into account information from countries' national report. Estimates of average regional biomass from these assessments are based on area-weighted, country-level means (derived from national inventories). This information could be used to inform policy makers about general rates and direction of change.

Reference: www.fao.org/forestry

US EPA Forest Inventory & Analysis (FIA)

Developed by the US Forest Service, the FIA is an annual survey that provides and collects information about national forests, and considers how these are likely to change over the next decades. FIA reports on status and trends on forest area and location; species, size, and health of trees; total tree growth, mortality, and removals by harvest; wood production and utilization rates by various products; and forest land ownership. The scope of the inventory has recently been expanded to include information on soils, under-story vegetation, tree crown conditions, coarse woody debris, and lichen community composition on a subsample of plots.

The Inventory consists of the following sources of information: A basic forest inventory using both remote sensing and data collection at sample locations distributed systematically across the landscape; Collection of forest health indicator data on a subset of the initial sample plots; Estimates of timber product output; National Woodland Owner Surveys and; National Assessments (every five years).

Reference: http://www.fia.fs.fed.us/

APPENDIX III: NON-EXHAUSTIVE SNAPSHOT OF EXISTING AND EMERGING INFORMATION DATABASES AND SYSTEMS

Name	Sponsor	Description	Status
Agriculture and Land Use National Greenhouse Gas Inventory Software (ALU)[145]	NREL, Colorado State University	• Provides a software program that guides an inventory compiler through the process of estimating emissions and removals related to agricultural and forestry activities • Applicable to: GHG emissions and sinks associated with biomass C stocks, soil C stocks, soil nitrous oxide emissions, rice methane emissions, enteric methane emissions, manure methane and nitrous oxide emissions and emissions from biomass burning • Consistent with IPCC guidelines	Launched and available online
Carboafrica[146]	Universities and multilateral agencies[147]	• Quantification, understanding and prediction of carbon cycle, and other GHG gases, in Sub-Saharan Africa. Objectives: • Consolidate and expand terrestrial carbon and other GHG fluxes monitoring network of Sub-Saharan Africa • Provide an analysis of the requirements in order to establish a terrestrial GHG monitoring systems for Sub-Saharan Africa • Understand quantify and predict the GHG budget of Sub-Saharan Africa and its associated spatial and temporal variability • Assess the current land use change and evaluate the potential for carbon sequestration in Sub-Saharan Africa in the context inter alia of the Kyoto Protocol	Launched 2006

[145] http://www.nrel.colostate.edu/projects/ghgtool/

[146] http://www.carboafrica.net/index_en.asp

[147] Università degli Studi della Tuscia, Max-Planck-Institute of Biogeochemistry, Lunds universitet (ULUND), Global Terrestrial Observing System, FAO (GTOS-FAO), Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Natural Environment Research Council Centre for Ecology and Hydrology (NERC), Consiglio Nazionale delle Ricerche (CNR-IBIMET), Instituto Agronomico per l'Oltremare (IAO), Seconda Università di Napoli (DSA-SUN), Council for Scientific and Industrial Research (CSIR), Unité de Recherche sur la Productivité des Plantations Industrielles (UR2PI), Agricultural Research & Technology Cooperation (ARC), Commissariat a l'Energie Atomique (LCSE) and Centre National de Recherche Scientifique (CNRS), King's College London (KCL), University of Leicester (ULEICS)

Name	Sponsor	Description	Status
Voluntary Reporting of Greenhouse Gases-Carbon Management Evaluation Tool (COMET-VR)[148]	Colorado State University, NREL, USDA, ARS, NRCS, US Forest Service	• Decision support tool for agricultural producers, land managers, soil scientists and other agricultural interests • Provides an interface to a database containing land use data from the Carbon Sequestration Rural Appraisal (CSRA) and calculates in real time annual carbon flux using a dynamic Century model simulation	Launched and available online
FRA 2010[149]	FAO	• Builds on existing FRA reports by adding a remote sensing survey • Purpose is to improve knowledge about land use dynamics (deforestation, afforestation and natural forest expansion).	Launched 2008
Global Carbon Monitoring System[150]	Australian Government with the Clinton Climate Initiative	• Develop national scale reporting systems projects that demonstrate the integration of remote sensing, models and measurement in developing countries • Develop web-based data delivery system allowing free and open access to an array of data from satellites, aircraft and field measurements.	2009
Global Land Cover Facility[151]	NASA, University of Maryland	• Encourage the use of remotely sensed imagery, derived products and applications within a broad range of science communities in a manner that improves comprehension of the nature and causes of land cover change and its impact on earth • Provide free access to an integrated collection of critical land cover and Earth science data through systems that are designed to maximise user outreach and promote development of novel tools for ordering, visualizing and manipulating spatial data	Late 1990's

[148] http://cometvr.colostate.edu/

[149] http://www.fao.org/forestry/44375/en/

[150] http://www.climatechange.gov.au/ncas/factsheets/fs-gcms.html

[151] http://www.landcover.org/index.shtml

Name	Sponsor	Description	Status
Globalsoilmap.net[152] and Africasoils.net	ISRIC – World Soil Information with the Bill & Melinda Gates Foundation & Alliance for a Green Revolution	*GlobalSoilMap.net* will not measure biomass stock and change; it will • Include soil organic C assessments at fine resolution (90 x 90m) for the entire globe. • Create a new digital soil map of the world using new technologies for mapping and prediction of soil properties at fine resolution • The first phase will prioritise mapping of African soils to 90m resolution, focussing on carbon, bulk density, clay content, water retention capacity[153]	Launched January 2009
Global Terrestrial Observing System (GTOS)[154]	WMO, UNESCO, UNEP, ICSU, FAO	Facilitates communication and cooperation between existing initiatives and promotes harmonization of measurement methods and data processing. Of particular interest, it hosts the Global Observation of Forest and Land Cover Dynamics panel (GOFC-GOLD). Expert groups help to establish key databases and regional networks.	Launched in 1999
Group on Earth Observations[155] Forest Carbon Tracking[156]	Various Government, multilateral agencies and universities	• Demonstrate that coordinated Earth Observations can provide the basis for reliable information services of suitable consistency, accuracy and continuity to support Forest Carbon Tracking. • Establishment of robust methodologies, satellite acquisition plans and a series of regional pilot studies, providing a template for roll-out of a consistent and reliable global carbon monitoring system • Start-up activities include: establishment of several regional reference test-sites, consolidation of observational requirements and associated products, secure coordination of observations, coordinated assessment of tools & methodologies at these sites, coordination of the production of reference datasets, improved access to observations, datasets, tools and expertise associated capacity building activities	Forest Carbon Tracking work plan launched 2009

[152] www.globalsoilmap.net

[153] Pers. Comm., Alfred Hartemink, ISRIC (16 March 2009)

[154] http://www.fao.org/gtos/

[155] http://www.earthobservations.org/about_geo.shtml

[156] http://www.earthobservations.org/documents/tasksheets/200901/cl-09-03b.pdf

Name	Sponsor	Description	Status
International Geosphere-Biosphere Programme[157]	Sponsored by various governments. Range of research institutions and multilateral agencies as partners.	Research programme to study the phenomenon of global change. Research goals include: • Analyze the interactive physical, chemical and biological processes that define Earth System dynamics • The changes that are occurring in these dynamics • The role of human activities on these changes	
LIFEWATCH[158]	Sponsored by various governments and research institutions	E-science and technology infrastructure for biodiversity data and observatories, including: • Facilities for data generation & processing, network of observatories, facilities for data integration & interoperability, virtual laboratories, service centre	2005
Planetary Skin[159]	Cisco Internet Business Solutions Group, NASA	• Global platform to monitor, analyse, verify and report on environmental conditions using data from variety of sources. • System will rely on 3 interlocking systems: *SensorFabric* (data collection), *DecisionSpaces* (data analysis), *CommonSpaces* (tool allowing management). • Rainforest Skin component will monitor deforestation (carbon stocks & flows)	Launched March 2009
The World's Forests: Design and Implementation of Effective Measurement and Monitoring[160]	Resources For the Future (RFF) with the Alfred P. Sloan Foundation	Assess advantages and limitations of existing technologies to measure forest area, timber volume, biomass and carbon sequestration capability	Framework launched 2009. Plan implementation to start 2010.

157 http://www.igbp.net/

158 http://www.lifewatch.eu/

159 http://www.planetaryskin.org/

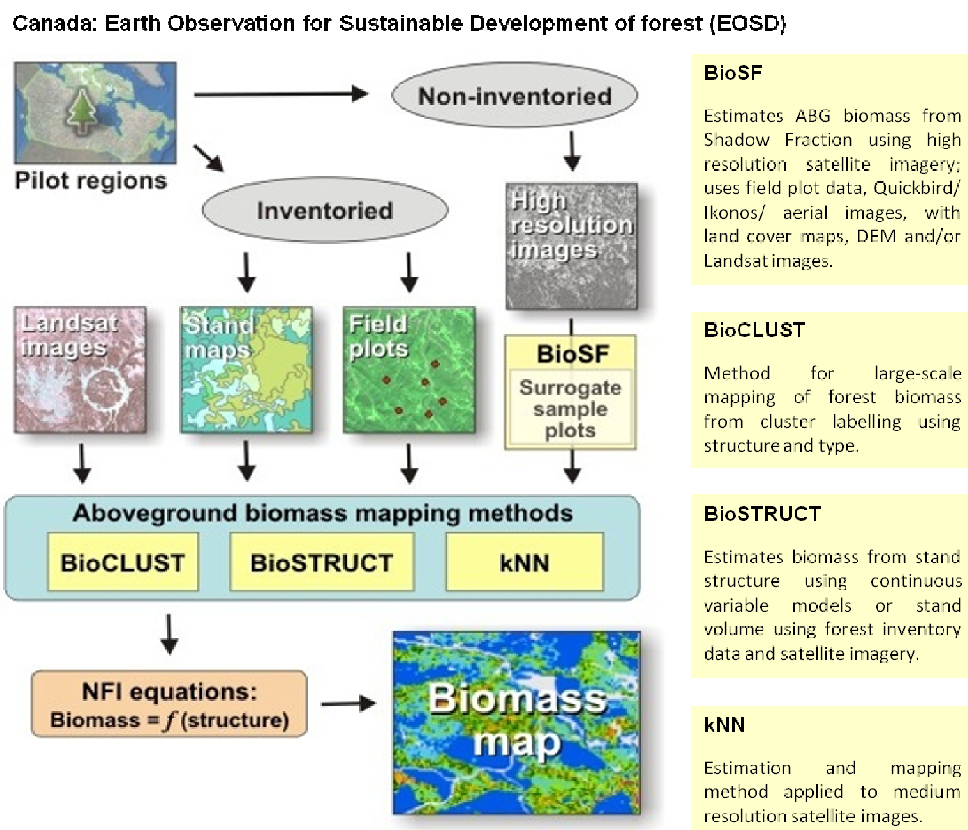
160 http://www.rff.org/News/Press_Releases/Pages/Forest_Measurement.aspx

Name	Sponsor	Description	Status
TREES[161]	Joint Research Centre (European Commission)	Target: to assess the evolution of tropical rainforest with a sample of medium resolution satellite images (Landsat TM). Possible development to examine other forest types (boreal).	1991

[161] http://bioval.jrc.ec.europa.eu/TREES/

APPENDIX IV: TWO EXAMPLES OF REMOTE SENSING APPLICATIONS

Canadian Earth Observation for Sustainable Development of forest (EOSD)



Reference: http://cfs.nrcan.gc.ca/subsite/eosd/home

The ECIDNA Lidar Scanner

The ECHIDNA laser scanner is a ground based, hemipsherically scanning lidar developed specifically for forest structural assessment. A scientific validation instrument has been constructed for use primarily in the research domain. In particular, The ECHIDNA Validation Instrument (EVI) is being validated for biomass assessment as part of NASA's Remote Sensing Science for Carbon and Climate program. Research in this field is focusing on assessment of woody biomass and green biomass with higher precision than customary field methods; and the linking of ECHIDNA lidar data, through a physical model, to airborne and space borne lidar measurements with the objective of mapping biomass over large areas remotely.[162]

---

[162] See: *Jupp, D.L.B., Culvenor, D.S., Lovell, J.L., Newnham, G.J., Strahler, A.H. and Woodcock, C.E. (2009). Estimating forest LAI profiles and structural parameters using a ground based lidar called 'ECHIDNA', Tree Physiology, 29: 171-181 and*

APPENDIX V: APPLICATIONS OF MODELS

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)

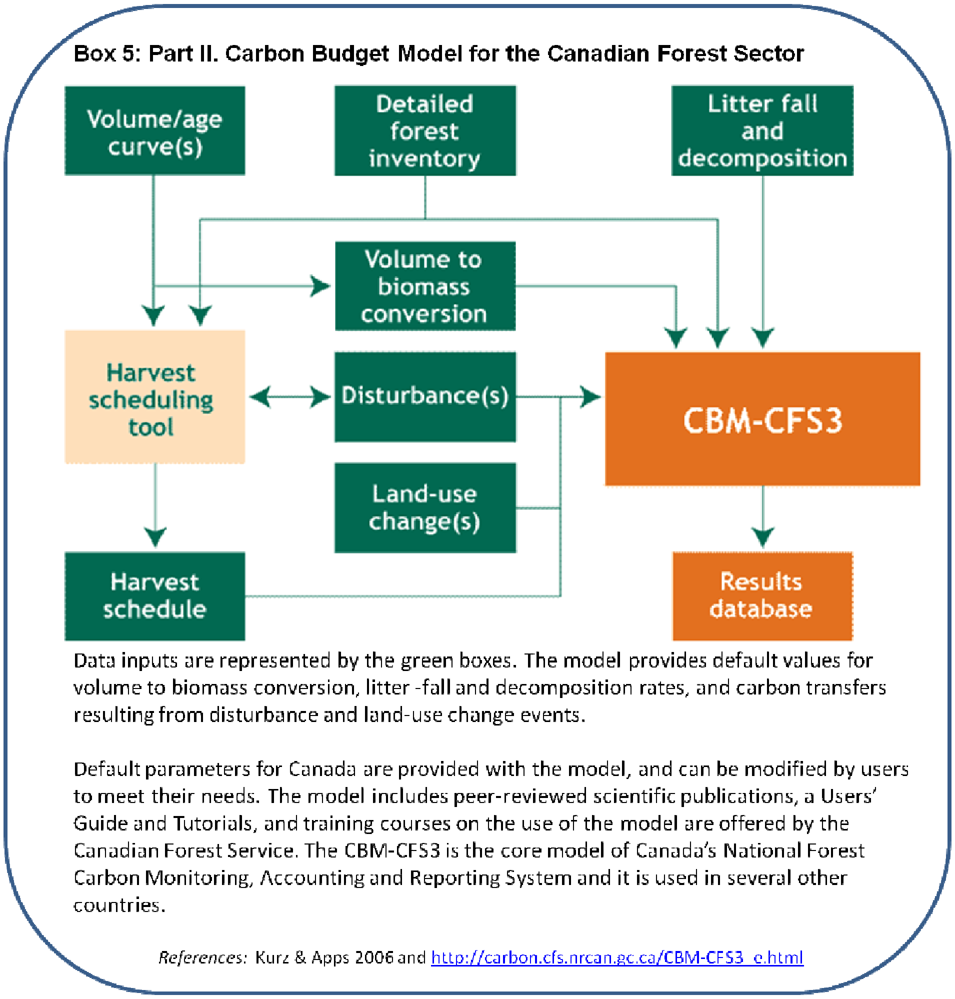
The CBM-CFS3 corresponds to an IPCC Tier 3 approach. It was developed by Natural Resources Canada, Canadian Forest Service, as an operational-scale carbon accounting tool. The CBM-CFS3 is an "aspatial, stand- and landscape-level modelling framework that simulates the dynamics of all forest carbon stocks required under the UNFCCC (ABG, BGB biomass, litter, dead wood and SOM)... The model requires much of the same information used for forest management planning activities (e.g. forest inventory data, tree species, growth and yield curves, natural and human-induced disturbance information, forest harvest schedule and land-use change information), supplemented with information from national ecological parameter sets and volume-to-biomass equations appropriate for Canadian species and forest regions".

This yield-driven model provides a spatially referenced, hierarchical system for integrating datasets originating from different forest inventory and monitoring programs and includes a structure that allows for tracking of land areas by different land use and land-use change classes. The model uses sophisticated algorithms to convert volume to biomass and explicitly simulates individual annual disturbance events (both natural and anthropogenic).

The model groups forest stands together into relatively homogeneous units – each stand is referenced to its spatial unit (broader strata delineated by administrative and ecological boundaries) but the exact location of each stand is not retained. The model tracks land-use class for each stand. Each stand is described by area (ha), age, land class, and up to 10 classifiers (defined by the model user) describing land characteristics including productivity, ownership and leading species. This can be overlaid with spatially relevant parameters. The system simulates annual changes in and between each pool within each stands' carbon stocks that occur due to growth, biomass turnover, litter fall, transfer and decomposition, and also simulates disturbances and forest management activities that alter the distribution of carbon among stocks and the post-disturbance dynamics.[163]

Strahler, A.H., Jupp, D.L.B., Woodcock, C.E., Schaaf, C.B., Yao, T., Zhao, F. Yang, X., Lovell, J., Culvenor, D., Newnham, G., Ni-Miester, W. and Boykin-Morris, W. (2008) Retrieval of Forest Structural Parameters Using a Ground-Based Lidar Instrument (Echidna®), Canadian Journal of Remote Sensing, 34: S426-S440

[163] *References:* Kurz et al Ecological Modelling 220 (2009), http://nofc.cfs.nrcan.gc.ca/bookstore_pdfs/29089.pdf, Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G. , Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards, Ecological Modelling 220: 480-504, doi:10.1016/j.ecolmodel.2008.10.018



Data inputs are represented by the green boxes. The model provides default values for volume to biomass conversion, litter -fall and decomposition rates, and carbon transfers resulting from disturbance and land-use change events.

Default parameters for Canada are provided with the model, and can be modified by users to meet their needs. The model includes peer-reviewed scientific publications, a Users' Guide and Tutorials, and training courses on the use of the model are offered by the Canadian Forest Service. The CBM-CFS3 is the core model of Canada's National Forest Carbon Monitoring, Accounting and Reporting System and it is used in several other countries.[164]

[164] *References:* Kurz & Apps 2006, Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G. , Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards, Ecological Modelling 220: 480-504, doi:10.1016/j.ecolmodel.2008.10.018 and http://carbon.cfs.nrcan.gc.ca/CBM-CFS3_e.html

Australia's National Carbon Accounting System, and Indonesia's National Carbon Accounting System

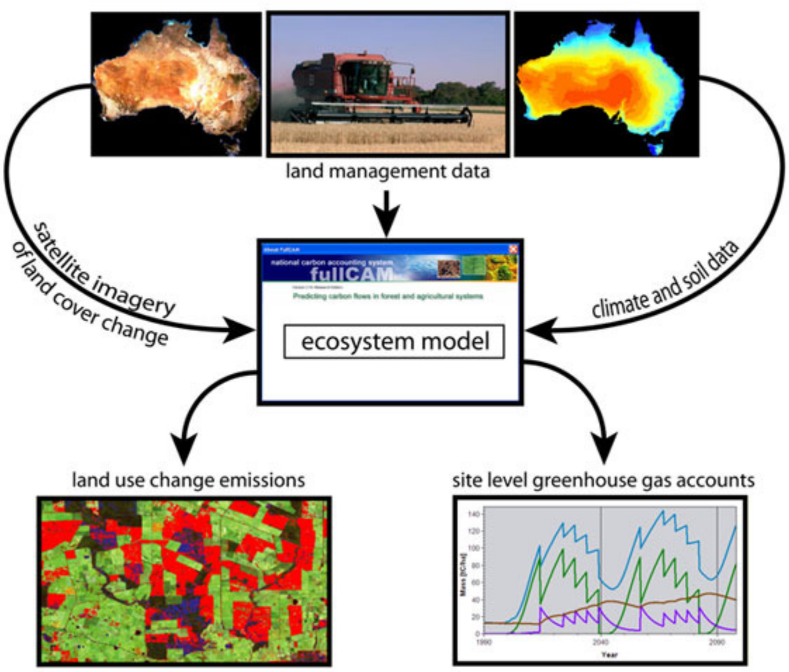
The following information is an extract from the Australian Government's website.[165]

Australia's National Carbon Accounting System (NCAS) is a world-leading system to account for greenhouse gas emissions from land based sectors.

Land based emissions (sources) and removals (sinks) of greenhouse gases form a major part of Australia's emissions profile. Around 27 per cent of Australia's human-induced greenhouse gas emissions come from activities such as livestock and crop production, land clearing and forestry. The removal of carbon dioxide from the atmosphere by forests provides an important greenhouse sink.

The NCAS accounts for these activities through a highly integrated system that combines:

- Remotely sensed land cover change (including mapped information from thousands of satellite images)
- Land use and management data
- Climate and soil data
- Greenhouse gas accounting tools, and
- Spatial and temporal ecosystem modelling.



NCAS development

[165] This information was obtained from: http://www.climatechange.gov.au/ncas/index.html

The NCAS was established in 1998 to provide a complete accounting and forecasting system for human-induced sources and sinks of greenhouse gas emissions from Australian land based activities.

It has been developed over several phases with its implementation driven largely by Australian Government policy and international reporting priorities. This approach has addressed the reporting capability for:

- The United Nations Framework Convention on Climate Change National Greenhouse Gas Inventories and Kyoto Protocol baselines
- Tracking of greenhouse gas emissions and removals from the land sector, and
- Projections of future emission trends.

A derivative of the NCAS — the National Carbon Accounting Toolbox (NCAT) — allows carbon accounting from land based activities at the project level. The NCAT is available free of charge, and allows users to track carbon dioxide emissions and removals using the same data and modelling that is used to create Australia's national greenhouse accounts.

Future directions

The NCAS is currently designed to account for carbon emissions from land based activities to meet national and international reporting requirements, as well as the project level through the NCAT. Ongoing development of the NCAS and the NCAT is focused on improving the capabilities of the system to account for non-carbon dioxide emissions such as methane and nitrous oxide from land based activities.

The NCAT is being further developed to improve its usability and provide low-cost project level greenhouse gas accounts.

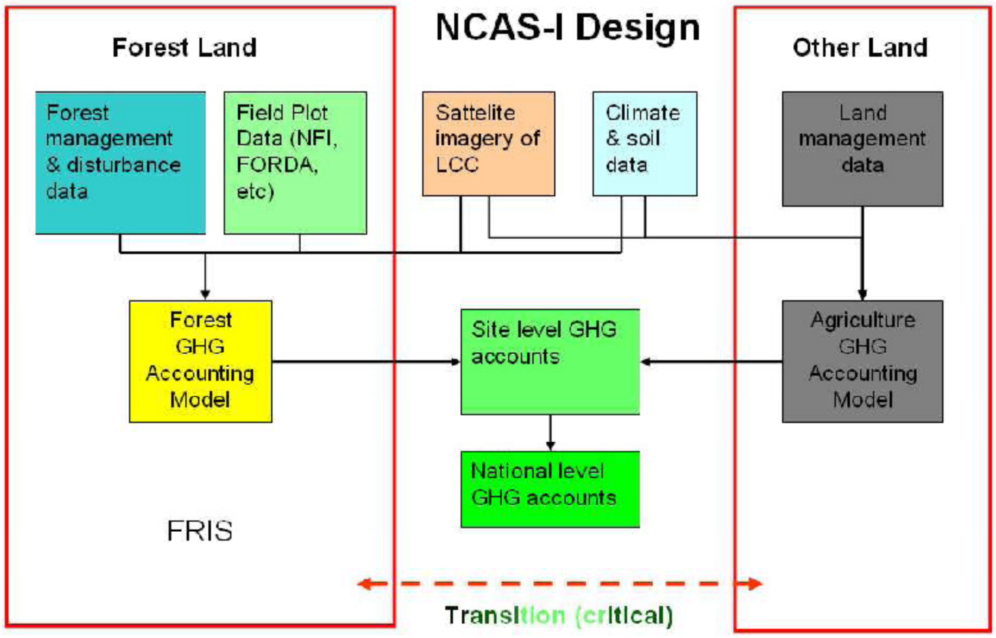
The extension of the NCAS into the international arena includes a collaborative approach with the Clinton Climate Initiative. This project aims to use the NCAS as a base for developing a global carbon monitoring system that can assist in recognising sustainable forestry and reforestation within global carbon markets.

Collaboration with Indonesia

The Republic of Indonesia is developing its own national carbon accounting system (“NCASI”) under its Forest Resource Information System (FRIS), with the capability to estimate emissions and sequestrations from forest management and disturbance, conversion, deforestation and degradation and afforestation. Under the Indonesia-Australia Forest Carbon Partnership, Australia will support the development of this system, and the two countries will share experiences with national-level accounting. The objectives of the Republic of Indonesia’s national accounting system are to:

- Provide monitoring capabilities for GHG emissions/sinks
- Establish a credible REL
- Support the development of policy and guidelines on GHG emissions/sinks and their mitigation from land based systems
- Reduce uncertainties that surround estimates of emissions and sinks
- Provide a scientific and technical basis to international negotiations including on REDD

The design of the system is described by the diagram below:



More information about the Partnership can be found at:
http://www.climatechange.gov.au/international/publications/pubs/indonesia-australia.pdf

Information on implementation, including a more complete of the diagram above can be found at:
http://www.dpi.inpe.br/geoforest/pdf/group2/04%20-%20National%20carbon%20accounting%20system%20of%20Indonesia.pdf