Integration of remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests

Methods and Guidance from the Global Forest Observations Initiative

Edition 2.0

GFOI

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GF🌳I

Dedication

For our dear friend and colleague Jim Penman. The voice of calm and intelligent reason, whom without this book would not be. Jim's contribution to the MGD, and more broadly the GFOI, has been vital in ensuring that the technical and scientific aspects of National Forest Monitoring Systems were always anchored in the policy needs of governments. The lasting value of the MGD will remain a perpetual tribute to his invaluable work on forests and climate change mitigation. Jim was a fine man, an intelligent and honest seeker of truth. He is sorely missed.

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Executive summary

The Global Forest Observations Initiative (GFOI) was established[1] by GEO in 2011, to assist countries to produce reliable, consistent reports on change in forest cover and forest use, and associated anthropogenic greenhouse gas emissions and removals.

The Initiative:

a. works with the Committee on Earth Observing Satellites (CEOS)[2] to facilitate long-term provision of satellite earth observation data to countries. CEOS has established the Space Data Coordination Group (SDCG) to address remote sensing requirements of GFOI

b. provides methodological advice on the joint use of remotely sensed and ground-based data to estimate and report greenhouse gas emissions and removals associated with forests in a manner consistent with the greenhouse gas inventory guidance from Intergovernmental Panel on Climate Change (IPCC). This is required by decisions of the United Nations Framework Convention on Climate Change (UNFCCC) for voluntary implementation of REDD+ activities[3]

c. identifies research and development[4] needs to improve data utility and the accuracy of national forest monitoring systems

d. helps countries to develop capacity to use earth observation data in national forest monitoring systems for reporting greenhouse gas emissions and removals[5].

Methodological advice and assistance with data access provided by the GFOI is of interest to countries wishing to use remotely sensed and ground-based data for forest monitoring and reporting. The current focus of GFOIs activities is to support countries wishing to report on reduced emissions from deforestation, forest degradation and associated activities, called REDD+ in the UNFCCC climate negotiations. The purpose of the Methods and Guidance Document (MGD) is to provide methodological advice identified in point b), linked to the data made available via the SDCG referred to in point a), and other relevant data. This is Edition 2 of the MGD. It updates Edition 1 (published in January 2014), taking account of recent developments including official REDD+ reference level submissions to the UNFCCC, increases in data availability and new research.

The intended users of the MGD are technical experts and policy colleagues:

User Group 1: working within the UNFCCC, who may be interested in how REDD+ activities can be described and linked to IPCC methodologies, as required by decisions of the Conference of Parties.

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[1] GFOI builds on the work of the earlier Forest Carbon Tracking (FCT) programme, established by GEO in 2008 to demonstrate that international cooperation can provide data and information useful for national forest monitoring and reporting.

[2] Established in 1984, CEOS coordinates civil space-borne observations of the Earth.

[3] The REDD+ activities as listed in the Cancun Agreements (UNFCCC Decision 1/CP.16 paragraph 70) are:

(a) Reducing emissions from deforestation; (b) Reducing emissions from forest degradation; (c) Conservation of forest carbon stocks; (d) Sustainable management of forests; (e) Enhancement of forest carbon stocks.

[4] The GFOI Research and Development document is available from the GFOI website

[5] The GFOI capacity building effort is currently lead by Silvacarbon and the UN-REDD program and complements readiness activities of the World Bank Forest Carbon Partnership Facility and the GOFC-GOLD programme supported by NASA through START.

User Group 2: responsible for the design and implementation of decisions to meet measurement, reporting and verification (MRV) requirements of national forest monitoring systems.

The MGD aims to increase mutual understanding between user groups, and with the relevant science, technical and policy communities, to guide the collection of relevant forestry data, and to assist sharing of data and experiences. It aims to complement the guidance from the IPCC (Chapter 2, Section 2.2), the approaches taken by the UN-REDD Programme, the World Bank FCPF and the GOFC-GOLD Sourcebook, and has been produced in cooperation with these initiatives.

The MGD complements IPCC guidance by providing advice based on the accumulated experience on the joint use of remote sensing and ground-based data, specific to REDD+ activities listed in the Cancun agreements[6]. Although guidance from the IPCC does treat deforestation in the Kyoto Protocol context[7], in general it does not identify REDD+ activities, as these were specified after the relevant IPCC guidance and guidelines were written. The MGD cross-references the IPCC guidance aiming not to repeat it unnecessarily.

Users may wish to take advantage of the availability of the MGD via REDDcompass which provides access to the most up-to-date GFOI advice, training materials and tools related to REDD+ MRV; and guides users through the various steps in setting up REDD+ reference levels and estimating emissions and removals associated with REDD+ activities.

While not explicitly addressed in the MGD, a well-designed and functional system for the measuring, reporting and verification of emissions for REDD+ can also be used to support:

▸ estimating emissions and removals from the broader Land Use, Land-Use Change and Forestry sector;

▸ internal reporting to assist with assessing the effects of domestic policies and actions;

▸ planning for other policy goals relevant to the land sector;

▸ generating information for country reports to the Global Forest Resource Assessment of the Food and Agriculture Organization of the United Nations.

The MGD chapters represent broadly the steps countries need to make in the development of estimates for reporting REDD+. Each chapter finishes with guiding principles, summarized as dot points. These are brought together here:

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[6] See decision 1/CP.16, paragraph 70

[7] See GPG2003 section 4.2.6

Chapter 1- Institutional Arrangements

▸ The important elements of a well-functioning institutional system are considered to be:[8]

 > a solid, sustainable network of institutions with the necessary range of expertise

 > clearly documented roles and responsibilities with a single body assigned for overall coordination

 > mechanisms for communication and exchange of information between central; and local, state, or provincial level agencies

 > continuity of staff and succession planning

 > high level of engagement and acceptance amongst the participating stakeholders.

▸ A long-term vision through strategic planning supported by adequate budgets should be established to support the development and ongoing monitoring, measurement, reporting and verification requirements of REDD+.

▸ Planning, preparation, documentation and archiving, compilation of reports, national consultation, assessment, approval, submission and continual improvement are MRV functions that require effective and documented institutional arrangements.

▸ Institutional arrangements established under REDD+ can also support broader reporting for the LULUCF sector, as well as greenhouse gas inventories for Biennial Update Reports.

Chapter 2 - Requirements and Design Decisions

▸ Well defined requirements and associated design decisions underpin the creation of a national forest monitoring and reporting system and should:

 > reflect decisions of the UNFCCC COP in setting the scope of REDD+ activities and the overall policy framework;

 > be consistent with methodological guidance developed by IPCC for greenhouse gas inventories for estimating greenhouse gas emissions and removals; and reflect efficient use of existing institutions and frameworks to minimize establishment and operational costs.

▸ National Forest Monitoring Systems (NFMS) should build on existing systems to make effective use of resources and provide data that are transparent and consistent over time, and suitable for Measurement Reporting and Verification including some or all of the following design decisions:

 > data collection, analysis, QA/QC and archiving processes

 > forest definition and stratification descriptions to enable land use/land cover reporting

 > consistency between reference levels, REDD+ reporting and GHGI reporting

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[8] These general principles were adapted from Gonzanlez Miguez, 2012; UNFCCC, 2013.For further discussion on institutional setup and case studies see: MAPT National GHG Inventory Case Study Series.

Chapter 3 - Methods and Approaches

▸ It is possible to specify systematically, REDD+ activity by REDD+ activity, methods to estimate emissions and removals in a way that links COP decisions and IPCC guidance.

▸ Integration frameworks can help organize data and estimation methods at any level of methodological complexity and facilitate the systematic progression from simpler to more complex methods.

Chapter 4 – Remote Sensing and Ground-based Observations

▸ In most cases estimates of emissions and removals associated with REDD+ activities will be made using a combination of remotely-sensed and ground based data.

▸ Landsat satellites provide a time series of remotely sensed digital images spanning 40 years and are being used widely in monitoring activities such as deforestation, forest degradation and natural disturbances, and for estimating changes in biomass and carbon stocks.

▸ Other types of remotely sensed data, such as SAR, LIDAR and high resolution optical data are increasingly available and helpful especially in extending the range of REDD+ activities for which operational methods are available.

▸ Pre-processed data sets can be used as a basis for REDD+ estimation in conjunction with reference and auxiliary data to capture national circumstances.

▸ Remotely sensed and auxiliary ground-based data in combination are likely to be useful for stratification in order to increase sampling efficiency.

▸ If sufficient NFI data are available over space and time and at sufficient spatial resolution, NFIs can be used to estimate directly from repeated inventories stock changes associated with REDD+ activities. It will often be best to use NFIs in combination with remotely-sensed data.

▸ Data from NFIs are also a potentially valuable source of information for REDD+ estimation using gain-loss methods, and for developing modelling approaches at Tier 3.

▸ Detailed information generated at a fine scale at intensive monitoring sites can help address the difficulty of estimating stocks and stock changes for litter, dead wood and soil, by supporting development of model parameters, including emissions and removals factors.

Chapter 5 - Estimation and Uncertainty

▸ Image classification can be by human interpretation, or it can be automated with human interpreters checking the results. The latter can be less resource intensive and may increase consistency.

▸ The results of using a classification algorithm can be improved by an iterative process involving human interpretation, choice of training data, and use of auxiliary information usually obtained via the NFMS on forest conditions on the ground.

▸ Reference data should be used with map data to correct for estimated bias and estimate confidence intervals.

▸ The stratification used for activity data and for estimating emissions and removals factors should be consistent.

▸ In addition to the general principles of consistent representation of land when using remote sensing for representing land or tracking units of land using a pixel approach, MGD advice is that:

   › Once a pixel is included, then it should continue to be tracked for all time. This will prevent the double counting of activities in the inventory and will also make emissions estimates more accurate.

   › Stocks may be attributed to pixels, but only change in stocks and consequent emissions and removals are reported with attention to continuity to prevent the risk of estimating large false emissions and removals as land moves between categories.

   › Tracking needs to be able to distinguish both land cover changes that are land-use changes, and land cover changes that lead to emissions within a land-use category. This prevents incorrect allocation of lands and incorrect emissions or removals factors or models being applied that could bias results.

   › Rules are needed to ensure consistent classification by eliminating oscillation of pixels between land uses when close to the definition limits.

▸ In addition to classification errors, uncertainties arise from biomass and other sampling used to establish emissions and removals factors and other parameters, and use of default data.

▸ Combining activity data and emission factor uncertainties to estimate overall uncertainty estimates is possible using repeated application of straightforward rules, or (in the case of more complex modelling approaches) by Monte-Carlo analysis.

Chapter 6 - Reporting and Verification of Emissions and Removals

▸ Effective reporting and verification processes require establishment of national capacity and good communication between the national institutions involved.

▸ Reporting and verification processes should aim for consistency in methodologies, definitions, comprehensiveness and the information provided between reported reference levels, results of the implementation of REDD+ activities and GHGI.

▸ Transparent, consistent, complete (in the sense of allowing reconstruction) and accurate data and information should be provided as part of the UNFCCC technical assessment and technical analysis processes.

▸ Sufficient information needs to be reported to enable third parties to be able to assess whether reporting requirements have been met.

▸ Internal and external technical experts should be used to assess the quality of information reported as well as of the overall effectiveness of the MRV system.

▸ Developing effective REDD+ reporting and verification can usefully be seen as part of a broader information system that supports sustainable development, and not simply as a necessity driven by COP decisions..

List of acronyms

2006GL	IPCC 2006 Guidelines
AD	Activity Data
AGB	Above-Ground Biomass
ALOS	Advanced Land Observing Satellite (Japanese series)
ALU	Agriculture and Land USE National GHG Inventory Software
A_{MNF}	Total Area of Modified Natural Forest
A_{PlantF}	Total Area of Planted Forest
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
AVNIR	Advanced Visible and Near Infrared Radiometer (Japanese series)
BUR	Biennial Update Reports
CBERS	China-Brazil Earth Resources Satellite series
CBM-CFS3	Carbon Budget Model of the Canadian Forest Sector
CB_{MNF}	Biomass Carbon Density for Modified Natural Forest
CB_{PF}	Biomass Carbon Density for Primary Forest
CO_2	Carbon Dioxide
$CO_{2degrad}$	Annual CO_2 Emissions from Degradation
CONAE	Comisíon Nacional de Actividades Espaciales (Argentine Space Agency)
COP	Conference of Parties to the UNFCCC
CNES	Centre Nationale d'Études Spatiales (French Space Agency)
CSA	Canadian Space Agency
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CRESDA	China Centre for Resources Satellite Data and Application
DMC	Disaster Monitoring Constellation
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
EROS	Earth Resources Observation and Science Data Center
ESA	European Space Agency
EXACT	Ex-Ante Carbon Balance Tool
FAO	Food and Agriculture Organization of the United Nations
FCPF	The World Bank Forest Carbon Partnership Facility
FLINT	Full Lands Integration Tool
FRA	Forest Resource Assessment
FREL	Forest Reference Emission Level
FRL	Forest Reference Level
FullCAM	Full Carbon Accounting Model
GFOI	Global Forest Observations Initiative
GHG	Greenhouse Gas or Greenhouse Gases
GIS	Geographical Information System
GLAS	Geoscience Laser Altimeter System
GOFC-GOLD	Global Observation of Forest Cover-Global Observation of Land Dynamics
GPG2003	Good Practice Guidance (IPCC 2003 Good Practice Guidance)
GREG	Model-Assisted Generalised Regression Estimator
IceSAT	Cloud and land Elevation Satellite
INPE	Instituto Nacional de Pesquisas Espaciais (Brazilian National Institute for Space Studies)
IPCC	Intergovernmental Panel on Climate Change

IRS	Indian Remote Sensing Satellite Series
ISRO	Indian Space Research Organization
JAXA	Japanese Aerospace Exploration Agency
KP	Kyoto Protocol
L1G	Landsat Level 1 Georectified
L1T	Landsat Level 1 Orthorectified
LAMP	LIDAR-Assisted Multisource Program
LANDSAT	Land Satellite (US Satellite series)
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
LIDAR	Light Detection and Ranging
LULUCF	Land use, Land-Use Change and Forestry
MGD	Methods and Guidance Document
MODIS	Moderate Resolution Imaging Spectroradiometer (US satellite series)
MNF	Modified Natural Forest
MRV	Measuring, Reporting, and Verification
NASA	National Aeronautics and Space Administration
NASRDA	Nigerian National Space Research and Development Agency
NCAS	National Carbon Accounting System (Australia)
NFI	National Forest Inventory
NFMS	National Forest Monitoring System
PF	Primary Forest
PlantF	Planted Forest
PSTR	Post-stratification
RADAR	Radio Distance and Ranging
RADARSAT	Canadian SAR satellite series
REDD+	Reducing Emissions from Deforestation, Reducing Emissions from Forest Degradation, Conservation of Forest Carbon Stocks, Sustainable Management of Forests, and Enhancement of Forest Carbon Stocks
SAOCOM	Argentine Microwaves Observation Satellite
SAR	Synthetic Aperture Radar
SLEEK	Systems for Land-based Emissions in Kenya
SPOT	Satellite Pour l'Observation de la Terre (French satellite series)
SRTM	Shuttle Radar Topography Mission
SRS	Simple Random Sampling
STR	Stratified Sampling
SYS	Systematic Sampling
TANDEM X	TerraSAR-X add-on for Digital Elevation Measurement (Germany)
TerraSAR X	SAR Earth Observation Satellite (Germany)
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UN-REDD	United Nations Collaborative Initiative on Reducing Emissions from Deforestation and forest Degradation (REDD). (Participating UN organizations are FAO, UNDP), and UNEP)
USGS	United States Geological Survey

Explanation of terms

Concept	Meaning	Notes	Example reference (where applicable)
Activity data	Data on the extent of human activity causing emissions and removals.	Activity data are often areas or changes in area.	Chapter 2; GPG2003, Vol 4, Chapter 3; 2006GL
Emission or removal factors	GHG emissions or removals per unit of activity data.		Chapter 3; GPG2003 Vol 4, Chapter 2; 2006GL
Forest Monitoring	Functions of a national forest monitoring system to assist a country to meet measuring, reporting and verification requirements, or other goals.		
Forest reference emission level or forest reference level	Benchmarks expressed in tonnes CO_2 equivalent per year for assessing each country's performance in implementing REDD+ activities	Need to maintain consistency with GHGIs	COP decisions 12/CP.17, 13/CP.19 and 14/CP.19

Concept	Meaning	Notes	Example reference (where applicable)
Greenhouse gas inventory	Anthropogenic greenhouse gas estimates with national territorial coverage produced using IPCC methods in accordance with decisions taken at the UNFCCC Conference of the Parties (COP).	Covers energy, industrial processes and product use, agriculture, forests and other land use and waste. The COP has agreed to base REDD+ emissions and removals estimates on the latest IPCC methods agreed for the purpose.	COP decision 4/CP.15 requests the use of the most recent IPCC guidance and guidelines as adopted or encouraged by the COP. Effectively in the REDD+ context Annex III, part III of decision 2/CP17 identifies these as the *Revised IPCC 1996 Guidelines* and the IPCC *Good Practice Guidance* 2000 and 2003. MGD also provides references to the 2006 Guidelines and supplements which presumably can be referred to on a voluntary basis. Decision 12/CP.17 requires FRELs and FRLs to maintain consistency with anthropogenic forest related emissions and removals in GHGIs and 14/CP.19 requires consistency between emissions and removals reported for REDD+ activities and FRELs or FRLs.

Concept	Meaning	Notes	Example reference (where applicable)
Ground-based data or ground-based observations	Data gathered by measurements made in the field.	Measurement of gaseous concentrations could also be regarded as remotely sensed if the point of measurement is distant from what is being measured.	
Mapping Data	Data used to produce maps	Generally remote-sensing although ground-based data can be used, subject to limitations of sampling intensity. Algorithms used to classify remotely-sensed data are subject to potential bias which can be addressed using statistical estimators which combine mapping and reference data.	
Measuring, Reporting and Verifying, also called Measurement, Reporting and Verification (MRV)	Procedures associated with the communication of all mitigation actions of developing countries.	Measuring is estimating the effect of the action, reporting is communication to the international community, and verifying is checking the estimation; procedures for all three are to be agreed by the UNFCCC.

Sometimes incorrectly called Monitoring, Reporting and Verifying. | Cancun Agreements (paragraphs 61 to 64, COP decision 1/CP.16; decision 14/CP.19 (Modalities for measuring, reporting and verifying). |
| **National Forest Inventory (NFI)** | A periodically updated sample-based system to provide information on the state of a country's forest resources. | Historically not linked to greenhouse gas emissions, but where it exists, a potential source of relevant data. | *National Forest Inventories,* Tomppo, E.; Gschwantner, Th.; Lawrence, M.; McRoberts, R.E. (Eds.), Springer 2010. |

Concept	Meaning	Notes	Example reference (where applicable)
National Forest Monitoring System (NFMS)	The arrangements in a country to monitor forests. NFMS will presumably include representation from responsible Ministries, indigenous peoples and local communities, forest industry representatives, and other stakeholders. In the REDD+ context, a system for monitoring and reporting on REDD+ activities, in accordance with decisions from the COP.	The COP has established that a NFMS should use a combination of remote-sensing and ground- based data, provide estimates that are transparent, consistent, as far as possible accurate, and that reduce uncertainties, taking into account national capabilities and capacities; and their results are available and suitable for review as agreed by the COP. NFMS may provide information on safeguards.	COP decisions 4/CP.15, 1/CP.16 and 11/CP.19 (Modalities for national forest monitoring systems).
Precision	How closely estimates of an underlying unknown true value from different samples agree with each other		
REDD+	Reducing emissions from deforestation; Reducing emissions from forest degradation; Conservation of forest carbon stocks; Sustainable management of forests; Enhancement of forest carbon stocks.		COP decision 1/CP.16.

Concept	Meaning	Notes	Example reference (where applicable)
Reference Data	The best available assessment of conditions on the ground for a given location or spatial unit. Reference observations can be used, for example, to estimate areas or carbon densities and associated standard errors based on sampling. Reference data are also used to assess the accuracy of maps made using remote sensing, and to correct for estimated bias. Reference observations may be accurately co-georeferenced ground data or finer resolution or more accurately classified remotely sensed data, which are available for a probability sample of the data-points with sufficient representation of classes of interest (e.g. changes associated with deforestation).	Reference data are generally collected according to probabilistic sampling design. This means that they can be used alone to produce estimates associated with REDD+ activities, or they can be used in combination with remotely-sensed mapping data to correct for classification bias. The latter approach may be most resource-efficient. Reference data are often ground-based data, though high quality remotely-sensed data can also be used.	
Remote Sensing	Acquiring and using data from satellites, aircraft or other platforms.	Measurement of gaseous concentrations could be regarded as remotely sensed if the point of measurement is distant from what is being measured.	Introductory Digital Image Processing: A Remote Sensing Perspective, Third Edition, John Jensen, 2004, Pearson

Concept	Meaning	Notes	Example reference (where applicable)
Safeguards	Undertakings to protect and develop social and environmental sustainability.	Covers consistency with national forest programmes and relevant international conventions and agreements; transparency and effectiveness of national forest governance; respect for the knowledge and rights of indigenous peoples and members of local communities; participation of relevant stakeholders, in particular indigenous peoples and local communities.	COP decisions 1/CP.16, 12/CP.17, 12/CP.19 and 17/CP.21.
Training Data	Used to calibrate remote sensing classification algorithms	Training data can be obtained from ground-based sources or from other remote sensing data, such as high resolution data.	

Purpose and scope

The GFOI MGD exists to provide countries with advice to support development of national forest monitoring systems (NFMS), and associated measurement, reporting and verification (MRV). The MGD focuses on how remotely sensed and ground-based data can be effectively combined to improve estimation of GHG emissions and removals from REDD+ activities. The MGD provides information that can be customised to fit individual country circumstances.

The MGD is relevant to all countries, but is mainly intended for technical decision makers and policy colleagues in REDD+ countries, as well as their partners in international agencies, multilateral and bilateral programmes. MGD advice addresses a gap that would otherwise exist in practical guidance on developing and implementing forest MRV, particularly the estimation of emissions and removals of GHGs from REDD+ activities. The MGD provides practical advice to help meet international reporting requirements by:

▸ providing a summary of the requirements of the IPCC guidelines and UNFCCC decisions about REDD+.

▸ presenting detailed advice to support decision making and technical implementation, and providing broad principles for the collection and use of data which will remain relevant even as technologies and methods evolve.

▸ illustrating how countries can apply the principles outlined in the document by using existing examples of national experience.

The term *guidance* is used in the MGD where there is a cross-reference to IPCC and *advice* is applied where complementary material is provided by the MGD. For example, IPCC's guidance recognizes the potential role of remote sensing in delivering GHG inventories. The MGD complements the IPCC guidance by providing advice based on global experience on the joint use of remote sensing and ground-based data, particularly in the REDD+ context.

Recognizing the needs of end users, the MGD:

▸ describes the process that countries need to work through to develop a system that meets national policy objectives

▸ uses decision trees and web links to help the user navigate and focus on material and tools relevant to them

▸ is provided in both printed and web-based formats[9].

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[9] The MGD web application REDDcompass provides online access to the MGD as well as a suite of MGD consistent training materials and tools.

The MGD recognizes the importance of MRV requirements and of national circumstances, for determining and mix of remote sensing and ground-based observations available to countries for REDD+ estimation. Relevant national circumstances, which may evolve over time, include the:

▶ level of engagement by government entities; national policy and reporting needs, including REDD+ reporting, mitigation planning and tracking of progress against targets

▶ history and drivers of forest use and conversion from forest to other land uses

▶ nature and availability of historical data, as well as meteorological factors such as cloud cover which can restrict the use of remote-sensing methods

▶ availability of ground data, including forest inventories, research and auxiliary data

▶ availability of technical expertise and institutional capacity to acquire and process data

▶ community, land-tenure, stakeholder, legal and administrative arrangements associated with forestry and other land uses and the level of engagement by stakeholders and decision makers

▶ available financial resources to design, build and operate MRV systems.

Chapter 1　Institutional arrangements

This chapter describes institutional arrangements and operational processes which support effective REDD+ implementation. It summarises various UNFCCC decisions relating to REDD+ that rely on sound institutional arrangements; highlights opportunities and challenges of the interdisciplinary nature of REDD+ and describes a range of measurement, reporting and verification processes and operational requirements.

1.1　Institutional arrangements and REDD+ decisions

Effective implementation of REDD+ activities requires sound institutional arrangements to support requirements set out in COP decisions[10] concerning (i) a national strategy or action plan; (ii) a national forest reference emission level and/or forest reference level (FREL/FRL); (iii) a robust and transparent NFMS[11] to meet MRV requirements for REDD+; and (iv) a system for providing information on safeguards[12].

The first step is the development of a long-term vision and a strategic plan, with clear institutional mandates and specification of roles and effective coordination mechanisms. Thorough processes should be established for collecting, processing, reporting and verifying data, based on methodologies and tools which recognise the need for adequate and sustainable human resource arrangements (Box 1: Institutional Arrangements).

In creating institutional arrangements to carry out the long-term vision and strategic plan, countries should build upon existing arrangements, such as those developed for greenhouse gas inventories (GHGI) that underpin National Communications. Building on and strengthening existing institutional arrangements in establishing a NMFS for REDD+ will reduce duplication of effort and costs, facilitate use of official data sources, avoid institutional conflicts and help maximise co-benefits and consistency in reporting.

An NFMS has two simultaneous functions; a monitoring function and an MRV function[13]:

1. **Monitoring function** - refers to a domestic tool that allows countries to assess a broad range of forest information including information specific to REDD+. Many forest-related monitoring tools already exist; it is important to build on existing tools, as appropriate, and to harmonize existing and new tools for forest monitoring for REDD+.

2. **MRV function** - refers to the estimation and international reporting of national-scale forest emission and removals for REDD+ drawing from information collected through the NFMS.

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[10] Chapter 2, Section 2.1 provides an extended summary of relevant COP decisions

[11] Or subnational monitoring arrangements as an interim measure see decision 1/CP.16, paragraph 71.

[12] As specified in decision 1/CP.16, paragraph 71

[13] National Forest-Monitoring Systems: Measurement, Reporting and Verification (M & MRV) in the Context of REDD+ Activities. Rome: Food and Agricultural Organization.

The UNFCCC has decided that a NFMS should[14]:

▶ build upon existing systems, as appropriate;

▶ enable the assessment of different types of forest (as relevant to the country's elected definition of forest) in the country, including natural forest, as defined by a country;

▶ be flexible and allow for improvement;

▶ reflect, as appropriate, the phased approach for the implementation of REDD+ activities.

Well-established arrangements that can deliver the MRV functions of an NFMS and be consistent with the above requirements can strengthen the design and evaluation of policies and actions, consistent with sound forest policy and governance (Box 2: Forest policy and governance). This will increase transparency in GHG reporting, facilitate financing, and lead to the quantification and reporting of mitigation actions in terms of emissions reductions and potentially other non-GHG impacts.

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[14] As specified in decision 11/CP.19

Box 1: Institutional Arrangements

The United Nations Development Programme (UNDP)[1] describes institutional arrangements as being policies, systems, and processes that organizations (including governments) use to legislate, plan and manage their activities efficiently and coordinate with others in order to fulfil respective mandates.

Institutional arrangements encompass the responsible organisations, their human resources, funding, equipment and supplies, leadership, effectiveness, and the communication links within and among organisations. Institutional arrangements support countries in translating complex technical findings into methodologically information that can be used for policy relevant purposes.

The UNFCCC has published a Toolkit[2] for non-Annex I countries on establishing and maintaining institutional arrangements for preparing national communications and biennial update reports. Though not specific to REDD+, the overall advice is relevant and important. These include that national institutional arrangements should help individual Parties ensure that nationally appropriate procedures for collecting, processing, reporting and archiving required data and information are established, and that relevant stakeholders from the public and private sectors are involved in meeting the reporting requirements of the Convention, as well as addressing the broader issue of climate change at the national level.

In particular, institutional arrangements can assist Parties to:

a) Meet reporting requirements under the Convention;

b) Develop and build national capacities and ensure sustainability and consistency of reporting processes

c) Inform national and international policymakers, at different levels

d) Assist in institutionalizing activities relating to reporting on climate change

Building effective sustainable institutional arrangements encompasses three key elements:

1. Institutions: Defining which institutions are involved in domestic MRV activities and what their respective roles and responsibilities are and how they should interact, how to intervene in case of challenges and who bears overall responsibility.

2. Processes: Defining the overall process of collecting, processing, reporting and verifying data. This includes determining which role individual institutions play within this process.

3. Methodologies and tools: Identifying which methodologies and tools are required to collect, process and store data.

Sources:

1. UNDP website has a range of resources on advice and experiences of establishing institutional arrangements

2. UNFCCC Toolkit for non-Annex I countries - establishing and maintaining institutional arrangements for a preparing national communications and biennial update reports

Box 2: Forest policy and governance

Institutional arrangements can strengthen the national policymaking process by enhancing coordination of all relevant stakeholders and by facilitating consultations and establishing relationships among technical and policy officials.

Prior to developing the MRV function for REDD+ activities, a country should identify national and regional development priorities and objectives that would serve as the basis for addressing REDD+ and climate change. This could involve strengthening forest governance (including law enforcement);developing measures to counter deforestation and forest degradation; and enhancing sustainable forest management through consideration of the multiple functions of forests (for example by considering both climate change mitigation and adaptation benefits). This process can lead to increased understanding of existing national challenges and available options for addressing GHG emissions and removals from REDD+ within the broader context of sustainable management of forests.

1.2 Institutions involved in measurement, reporting and verification

Given the interdisciplinary nature of REDD+, several government agencies, and non-government organisations and institutions and community stakeholders may be involved in the design, development and operation of MRV functions. Clearly-designated roles and responsibilities for managing and monitoring REDD+ emissions and removals will help avoid confusion and assist in efficient delivery of information nationally and internationally. Ideally, the agency responsible for REDD+ estimates should be the same as the agency providing forest-related estimates of emissions and removals for the GHGI, or there should be close coordination between the agencies involved, with the arrangements and responsibilities clearly documented (e.g. via Memoranda of Understanding).

UNFCCC decisions suggest that a national focal point[15] could have overall responsibility for coordinating the REDD+ MRV function and liaising with the UNFCCC. The national focal point should be identified as soon as possible to avoid ambiguity among stakeholders concerning the role and responsibility of this lead position.

In addition to the national focal point, an institutional body will be required to manage the work of institutions and organizations; and have overall responsibility for the coordination of administrative and technical arrangements, and the overall quality of reported estimates. Unless there are good reasons otherwise, the national focal point should belong to this institutional body, and the national focal point for REDD+ should work closely with the agency tasked with implementation.

Mandates are important to clarify roles, responsibilities, accountabilities and direct particular institutions to provide data or perform specific tasks. These arrangements should help minimize difficulties in resource allocation, both human and financial. These mandates should specify how REDD+ institutions and stakeholders will work with those responsible for national GHGIs.

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[15] Decision 10/CP.19, states that countries could "designate, in accordance with national circumstances and the principles of sovereignty, a national entity or focal point to serve as a liaison with the secretariat and the relevant bodies under the Convention, as appropriate, on the coordination of support for the full implementation of activities and elements referred to in decision 1/CP.16, paragraphs 70, 71 and 73, including different policy approaches, such as joint mitigation and adaptation, and to inform the secretariat accordingly".

Opportunities and obstacles on data accessibility and institutional arrangements are country-specific and so require tailored responses at appropriate levels. Although a single institution might be responsible for the NFMS, many actors need to be involved in the different components of the system, such as data collection and management, monitoring and measuring GHG emissions as well as reporting and verifying emissions reductions. Consequently, responsibilities for the different elements of the NFMS may lie with various institutions, or divisions and departments within them. Coordination requires clarification of each organization's responsibilities within national institutional arrangements, with clear written mandates. Such coordination should facilitate both national and international reporting processes including for instance the preparation of BURs or National Communications to the UNFCCC. A decision tree identifying the role of institutional coordination in establishing consistency between GHGIs and REDD+ estimated in the context of FRELs and/or FRLs is presented in Chapter 2, Section 2.3.3.

In the context of both GHGIs and REDD+ MRV requirements, data-sharing agreements have been used by some countries and institutions, often as an interim solution before comprehensive NFMS institutional arrangements are established. The flexibility of data sharing agreements (in terms of the number of parties and scope) helps accommodate specific requirements which can evolve over time, offering a tailored solution to the issue of data accessibility.

1.3   Measurement, reporting and verification processes

MRV functions that require effective and documented institutional arrangements can be clustered into seven key stages (Figure 1: MRV functions requiring effective and documented institutional arrangements). The corresponding processes apply to the preparation of FREL/FRL submissions as well as to the preparation of data and information for the REDD+ Annex to BURs.

In an effective NFMS these MRV processes are built on an in-depth design phase (Chapter 2) taking into consideration national and international reporting requirements (Chapter 6) and their periodic nature. These processes should be considered programmatic; learning from strengths and weaknesses identified as MRV experience accumulates in a continuous improvement process.

Figure 1: MRV functions requiring effective and documented institutional arrangements

Source: Modified from UNFCCC Toolkit for non-Annex I countries - establishing and maintaining institutional arrangements for preparing national communications and biennial update reports
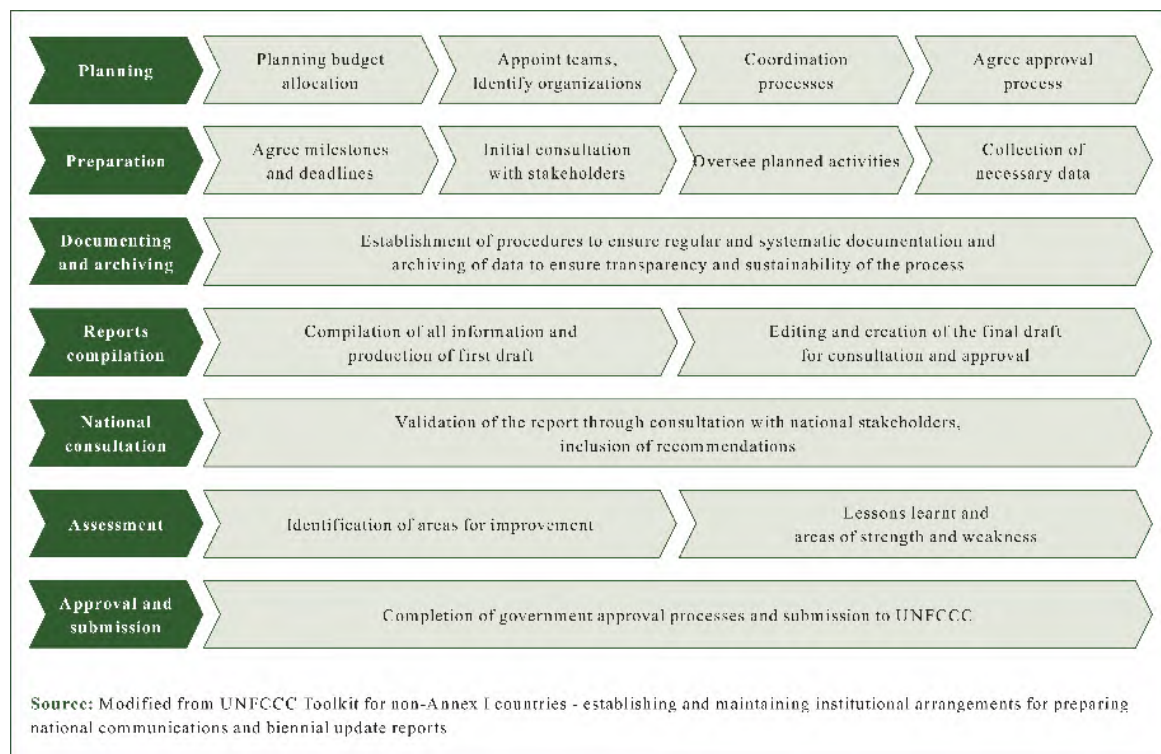
Successful implementation of these processes requires recruitment and retention of qualified staff, and sufficient established positions. Sustaining sufficient human resource capacity is long-term and should have a base in national institutes, organisations and academic establishments. One-off or periodic training initiatives can be helpful but their long-term benefit is likely to depend on having a sustained basis. There should be sufficient funding to help to minimize staff turnover and for training of staff (including students and young professionals) at national, subnational and sectoral levels.

Documented decisions on scope, long term management approaches (Box 3: Measurement, reporting and verification management options) and desired outcomes assist in effective MRV budget setting, system operation and continuous improvement.

Box 3: Measurement, reporting and verification management options

Centralized vs. decentralized: The country's lead agency may maintain most control and decision-making authority. A centralized approach will probably include relatively few other institutions. By contrast a decentralized approach may include many different teams and/or institutions. Countries with a large administration and various institutions with relevant expertise are more likely to use the decentralized approach. In this case, the lead agency will have an essential coordinating role to ensure that consistency between methodological decisions made by different teams and/or institutions involved.

In-sourced vs. out-sourced: Government agencies and employees may prepare most, or all, of the REDD+ estimates, thus in-sourcing the process. Alternatively, the government may out-source the work to consultants, research organisations, academic institutions, or NGOs. Out-sourcing can be useful depending on the availability of in-sourced expertise, but has risks because out-sourced expertise may not be well integrated with government processes, may not continue to be available, and may give conflicting advice. To be useful outsourced expertise should be coupled with development of capacity of NFMS agencies with the aim of maintaining consistency and sustainability over time, particularly in respect of managing out-sourced resources whilst in-source capabilities are being developed.

Single agency vs. multi-agency: The lead agency may be housed within a single government agency, or the country's lead body may be composed of a multi-agency working group, committee, or other structure. Multi-agency structure requires clear delineation of roles and responsibilities to ensure that there is a clear line of reporting and decision-making on REDD+ estimation. Although the multi-agency approach may have some relative advantages in regard to plurality in the decision-making process, in practice it is usually best if one agency has the overall coordinating role to avoid conflicts.

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

Source:

Hewson, J.,M.K. Steininger & S. Pesmajoglou. (Eds.) (2014). REDD+ Measurement, Reporting and Verification (MRV) Manual, Version 2.0. USAID supported Forest Carbon, Markets and Communities Program. Washington, DC, USA.

1.4 Operational requirements

Technical operational requirements and national circumstances can influence the design of institutional arrangements. At an operational level methodologies and tools will often encompass a combination of remote sensing and field-based forest carbon inventory approaches for the estimation of anthropogenic forest-related GHG emissions by sources and removals by sinks, forest carbon stocks and forest area changes[16] associated with REDD+ activities. The methodologies and tools may also provide relevant

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[16] See decision 4/CP.15 and 11/CP.19

information for national systems for the provision of information on how safeguards are addressed and respected[17].

Development and implementation of methodologies and tools require a range of skills and expertise to enable monitoring and reporting to be consistent over time. For effective operation, institutional arrangements should establish frameworks for:

- formalising mandates for data acquisition, processing and sharing amongst relevant institutions to set out responsibilities and avoid duplication of efforts

- maintaining documented processes for quality assurance and quality control, so as to ensure the quality datasets (e.g. for spatial data and carbon pool measurements)

- continual improvement including documentation of opportunities for improvement and process for the inclusion of such improvements

- retaining skilled staff through appropriate and ongoing training and environments to encourage staff retention

- securing adequate budgets to support the initial development of the MRV function as well as the ongoing operation and development.

Regular assessment of elements such as cost effectiveness, expectations, adequacy of processes and planning, possible improvements and expansions against the identified vision, objectives and strategic direction of the programme is recommended. This continuous improvement assessment could form part of the institutional arrangement processes.

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[17] see decision 1/CP.16, Appendix I

Box 4: Institutional arrangements – Examples from South America

In Colombia, the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) assisted by UN-REDD is producing a report containing the analysis of legal and institutional elements for the implementation of the NFMS, in order to develop an appropriate legal instrument (decree, or regulation) to regulate the functioning of the NFMS. The major aspects refer to the need to clarify roles and responsibilities of each institution involved, such as the Ministry of Environment and Sustainable Development, to develop inter-institutional coordination mechanisms and to define clear agreements between the relevant institutions to share data. Steps envisaged are to: a) analyse the forest legal framework focusing on NFMS aspects, and identify existing provisions related to the institutional framework defining roles and responsibilities at national and local level, b) define gaps and inconsistencies in the legal framework, and elaborate recommendations to improve it, c) consult with relevant stakeholders to understand their main challenges, d) identify existing platforms that might facilitate the exchange of data in the establishment of a NFMS, e) share the final legal report with the competent institutions and actors for its validation and f) identify options of legal reforms to be adopted in the short term or the legal instrument to be enacted.

In Honduras, a similar process is ongoing led by the Secretary of Energy, Natural Resources, Environment and Mines (Mi-Ambiente) and the National Institute of Forest Conservation and Development, Protected Areas and WildLife (ICF) and assisted by UN-REDD.

Some countries in Latin America are currently exploring the possibilities and alternatives in establishing or strengthening arrangements among institutions in a broader framework of land monitoring, including the agriculture ministries and institutes in the dialogues.

In Guyana, work started on the implementation of REDD+ in 2008, with a review of existing roles, and a definition of the planned responsibilities, for key partners. Subsequently, a road map for the development of the MRV function for REDD+ participation was designed.

As the agency responsible for monitoring and managing Guyana's state forests, the Guyana Forestry Commission (GFC) was identified as the focal point and lead for the implementing the key technical aspects of REDD+, including the development of the MRV function. A REDD Secretariat was subsequently established within the GFC to coordinate and implement technical activities related to REDD+ nationally, including work on the MRV function. REDD+ activities were designed to build on Guyana's previous efforts in terms of national forest monitoring and forest management. Building upon this technical work, Guyana adopted an integrated, multi-sectoral approach to REDD+ implementation, incorporating the country's other natural resource management agencies, the private sector, civil society, academic and training institutions, and NGOs Indigenous and Environmental. The Office of Climate Change was established with the role of providing policy advice on REDD+. These arrangements served to reflect the multifaceted approached required for REDD+ implementation.

An MRV Steering Committee comprised of representatives from government, private sector, indigenous representation, and academia, was convened to foster a multi-stakeholder development and implementation approach. This committee oversees coordination of MRV datasets and oversees the technical development process. As a related objective, the Steering Committee is responsible for providing a mechanism to support the boarder objectives of land use and land management (including within forest areas), in Guyana.

So far these structures, both coordinating and decision making, have effectively allowed for a flow and exchange of information and decisions. Further, there continues to be the expansion of the physical and technical capacity of each of the institutions responsible for implementing and maintaining aspects of both REDD+ and the MRV function and ensuring that implementation is internationally accepted and scientifically supported.

1.5 Guiding principles − Institutional arrangements

▸ The important elements of a well-functioning institutional system are considered to be:[18]

  › a solid, sustainable network of institutions with the necessary range of expertise

  › clearly documented roles and responsibilities with a single body assigned for overall coordination

  › mechanisms for communication and exchange of information between central; and local, state, or provincial level agencies

  › continuity of staff and succession planning

  › high level of engagement and acceptance amongst the participating stakeholders.

▸ A long-term vision through strategic planning supported by adequate budgets should be established to support the development and ongoing monitoring, measurement, reporting and verification requirements of REDD+.

▸ Planning, preparation, documentation and archiving, compilation of reports, national consultation, assessment, approval, submission and continual improvement are MRV functions that require effective and documented institutional arrangements.

▸ Institutional arrangements established under REDD+ can also support broader reporting for the LULUCF sector, as well as greenhouse gas inventories for Biennial Update Reports.

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[18] These general principles were adapted from Gonzanlez Miguez, 2012; UNFCCC, 2013.For further discussion on institutional setup and case studies see: MAPT National GHG Inventory Case Study Series.

Chapter 2   Requirements and design decisions

Starting with COP decisions[19], this chapter describes related policy, institutional and methodological frameworks and provides advice on how to combine them. It considers use of existing information, methodological choice and associated implications for reference levels, the role of subnational approaches and cost effectiveness.

2.1   UNFCCC decisions and requirements

A country's approach to estimation and reporting of REDD+ activities is influenced by UNFCCC COP decisions; GHGI methods produced by the IPCC; and national circumstances including those related to NFMS and forest definitions. As part of the UNFCCC Warsaw Framework for REDD+, decision 14/CP.19, sets out MRV modalities as they apply to REDD+. Decision 14/CP.19 recalls previous decision 4/CP.15, which amongst other things requests Parties to use:

▸ the most recent guidance of the IPCC, as adopted or encouraged by the Conference of Parties, as appropriate, as a basis for estimating anthropogenic emissions and removals associated with REDD+ activities

▸ a combination of remote-sensing and ground-based data.

Decision 14/CP.19 recognizes the need to develop capacity; that data and information used by Parties to estimate anthropogenic emissions and removals associated with REDD+ activities need to be transparent, consistent over time, and consistent with the FRELs and FRLs submitted by Parties under another decision, 12/CP.17. Decision 14/CP.19 encourages improvements of data and methodologies, maintaining consistency with FRELs and FRLs. Parties seeking results-based payments for REDD+ activities are requested to provide a technical annex to their biennial update reports (BUR). This annex is to include:

▸ information on FRELs and FRLs,

▸ the results of the implementation of the REDD+ activities expressed in tonnes of carbon dioxide equivalent per year (tCO$_2$eq/yr),

▸ demonstration of consistency between results and FRELs and FRLs,

▸ information that allows recalculation of results, and

▸ a description of the NFMS.

The information contained in the technical annex will be analysed by the Technical Team of Experts under the UNFCCC International Consultation and Analysis (ICA) process[20] (Chapter 6, Section 6.5).

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[19] For a complete understanding of the REDD+ agreement reached at COP19, and previous and subsequent decisions consult the full text of the decisions which can be accessed from the UNFCCC web-site

[20] The COP, by decision 1/CP.16, decided that developing countries would submit biennial update reports (BURs) (paragraph 60) and conduct international consultation and analysis (ICA) of the BURs (paragraph 63), through technical analysis by a team of technical experts (TTE) and facilitative sharing of views. The BUR reporting guidelines for Parties not included in Annex I to the Convention (non-Annex I Parties) as well

The outcome of the analysis is published with areas for improvement identified. COP19 agreed that further verification modalities may be required in the context of market-based approaches. More information on reporting and verification of results is presented in Chapter 6.

Decision 11/CP.19 on NFMS reaffirms the link to the most recent IPCC guidelines and guidance adopted or encouraged by the COP. NFMS should provide data and information that are transparent, consistent over time, suitable for MRV of REDD+ activities, and consistent with decisions on nationally appropriate mitigation actions (NAMAs). NFMS should build on existing systems, enable assessment of different forest types, including natural forest, as defined by a country, be flexible and allow for improvement. NFMS should reflect, as appropriate, a phased approach. Previous decision 1/CP.16, paragraphs 73 and 74, established that a phased approach begins with development of national strategies or action plans, policies and measures and capacity-building, is followed by their implementation and possibly further capacity-building, technology development and transfer and results-based demonstration activities, and evolves into results-based actions that should be fully measured, reported and verified[21]. Decision 11/CP.19 acknowledges that NFMS may provide, as appropriate, relevant information for national systems for the provision of on how the safeguards set out in appendix 1 to Decision 1/CP.16, are addressed and respected. Decision 12/CP.19 establishes that this information on safeguards should be provided via National Communications, and (on a voluntary basis) via the REDD+ Web Platform on the UNFCCC web site, once implementation of REDD+ activities has begun, and as a prerequisite to obtain and receive results-based payments. COP 21 agreed decision 17/CP.21 with strong encouragement on elements to include where appropriate when providing summary information on safeguards.

In 2011, decision 12/CP.17 established that FRELs and/or FRLs are benchmarks for assessing performance in implementing REDD+ activities. They should be set transparently, taking into account historical data, may be adjusted for national circumstances, and should maintain consistency with anthropogenic emissions and removals estimates as contained in each country's GHGI. Decision 12/CP.17 invited developing countries to submit reference levels, on a voluntary basis. In 2013 the COP decided in decision 13/CP.19 that the FRELs and FRLs submitted under decision 12/CP.17 shall be subject to technical assessment. An annex to decision 13/CP.19 provides information on the scope of the assessment; which includes consistency with emissions and removals estimates contained in the GHGI, how historical data have been used, transparency, completeness and accuracy, consistency of the forest definition with that used for other international reporting, inclusion of assumptions about future changes to domestic policies included in reference levels, activities, pools and gases included and justification concerning why omitted activities and pools were deemed not significant, and updating of information which is contemplated in decision 12/CP.17 by the stepwise approach.

Several FREL and FRL submissions, and the associated technical assessments, are available[22] and Section 2.3.3 provides advice on the interpretation of technical terms associated with FRELs and FRLs .

Emissions and removals from REDD+ activities are quantified in the context of the national GHGI, reported through the BURs[23], and performance measured against national FRELs and/or FRLs.

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as the modalities and guidelines for ICA were adopted at the seventeenth session of the Conference of the Parties (COP 17), by decision 2/CP.17 in annexes III and IV respectively.

[21] See paragraphs 73 and 74 of decision 1/CP.16

[22] See the REDD+ platform on the UNFCCC web-site

[23] See Chapter 6 on reporting and verification

Implementation at the national level reduces concerns about displacement[24] associated with project level engagement. Subnational demonstration activities (those which do cover a significant area but not extend to full national coverage), including subnational forest monitoring, are recognized as a possible interim step to national REDD+ implementation[25]. According to decision 1/CP.16, full implementation of results-based actions requires national forest monitoring systems and full MRV[26]. There are some additional issues raised by subnational coverage e.g. at state, province or project level. For example the need to include monitoring and reporting of emissions displacement at the national level, if appropriate, and reporting on how displacement of emissions is being addressed, and on the means to integrate subnational monitoring systems into a national monitoring system[27]. When establishing subnational systems it is important to consider how the system will be eventually included consistently within the final national system, and which components (in particular remote sensing) can be used at the national level for subnational estimates.

Decision 15/CP.19 recognizes the importance of addressing drivers of deforestation and forest degradation. It recognizes their complexity, and their linkage to livelihoods, economic costs and domestic resources. Parties, relevant organisations and the private sector are encouraged to work together to address drivers of deforestation and forest degradation, and to share information including via the UNFCCC REDD+ Web Platform. From a technical perspective, quantification of the effect of drivers on emissions and removals requires gathering evidence on the effect of direct causes such as pressure from commercial or subsistence agriculture, commercial timber extraction, fuel-wood collection and charcoal production, conservation and sustainability policies and other policy drivers. Taking drivers into account may be useful in stratification of lands, in ensuring consistency between historical data and reference levels and (in the case of subnational FRELs and FRLs, in monitoring displacement as required by the footnote to paragraph 71(c) of decision 1/CP.16, the Cancun Accords.

Decisions 9/CP.19 and 10/CP.19 repeat the need for adequate and predictable support for the implementation of REDD+ activities, establish a process for coordination of support, and link results-based finance to MRV and the provision of safeguards information. Decision 9/CP.19 encourages support from a wide variety of sources, including the Green Climate Fund (GCF), taking into account different policy approaches. It also requests use of the methodological guidance consistent with COP decisions, and requests the use of this guidance by the GCF when providing results-based finance. COP21 agreed decision 18/CP.21 that identifies the importance of incentivizing non-carbon benefits associated with REDD+ activities, and invites developing countries to share relevant information for consideration by Parties and financing entities, though these issues are not a requirement for support or results-based payments.

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[24] Displacement (also called leakage is the effect of the forest activity in increasing emissions (or reducing removals) outside the area monitored. National approaches help deal with displacement because the whole country is covered. Where project approaches simply monitor the project area the risk of missing emissions due to displacement is higher.

[25] Implementation of national REDD+ policies will often require engagement at local, state or department levels. The point is there should be national monitoring, possibly with sub-national monitoring as an interim step, for the reasons given.

[26] See decision 1/CP.16, paragraph73, 77 and footnote 8. Funding at earlier stages may be provided for capacity building, development of national strategies and action plans and their implementation, technology development and transfer and results-based demonstration activities. See the full list in paragraph 73.

[27] See decision 1/CP.16, paragraph 71, footnote 7

2.2   IPCC good practice guidance

Since 1996, the IPCC has published the methodological guidance that countries have agreed to use in estimating GHGIs for reporting to the UNFCCC and the KP. Table 1: Versions of IPCC guidance summarizes the methodological guidance introduced by IPCC since 1996, covering all sectors including those related to land use.

Table 1: Versions of IPCC guidance

IPCC Guidance Document	Description
1996 Revised IPCC Guidelines for National Greenhouse Gas Inventories (96GL)	First guidelines agreed for use under the UNFCCC
2000 Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (GPG2000)	Provides good practice guidance in implementing the 1996 Revised Guidelines. Covers all sectors except land use, land-use change and forestry. Introduces the definition of *good practice* – retained by all subsequent guidance and guidelines.
2003 Good Practice Guidance for land use, land- use change and forestry (GPG2003)	Extends good practice guidance to include land use, land-use change and forestry.
2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006GL)	Consolidates and updates previous guidance. Uses the same methodological framework as GPG2003. Combines agriculture and land use into a single sector (Agriculture, Forestry, and Other Land Uses or AFOLU).
2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands	Fills gaps and extends the 2006GL and updates emission/removal factors including on wetlands and drained soils
2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol	Provides guidance in support of the LULUCF accounting rules agreed for LULUCF for the second commitment period of the KP

2.2.1   Relationship to UNFCCC

There is a well-established system under the UNFCCC and the KP for reviewing inventories of developed countries, and this is the basis for assessing progress towards emissions reduction targets and commitments. As indicated above, COP decisions require consistency between FRELs/FRLs, GHGI and REDD+ emissions and removals estimates to be assessed as a requirement for participation in incentive schemes.

In 2011 the UNFCCC decided[28] that the 96GL in conjunction with the GPG2000 and GPG2003 should be used by developing countries for estimating and reporting anthropogenic emissions and removals.

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[28] See decision 4/CP.15 and Part III of Annex III to the Durban Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention (decision 2/CP.17), developed countries will use the 2006GL

As a consequence for REDD+, the inventory framework in which GFOI operates is effectively defined by the GPG2003. The MGD therefore cross-references the GPG2003. Countries can presumably use scientific updates in the 2006GL within this framework, and so the MGD also provides references to corresponding sections of 2006GL and the 2013 Wetlands Supplement. In 2015 the UNFCCC Subsidiary Body for Implementation noted the requests from non-Annex I Parties for training on the use of the 2006GLs, which may also be used for REDD+ (paragraph 29 of document FCCC/SBI/2015/10).

The concept of good practice underpins the GPG2003 and the 2006GL. Good practice is defined by IPCC[29] as applying to inventories that contain *neither over- nor under-estimates so far as can be judged, and in which uncertainties are reduced as far as is practicable*. Although there is no pre-defined level of precision, this definition aims to maximize precision without introducing bias, given the level of resources reasonably available for GHGI development. This level of resource is implicitly understood by the international inventory review and technical assessment processes administered by the UNFCCC and outlined in context of REDD+ in Chapter 6.

Good practice covers cross-cutting issues relevant to GHGI development, including data collection including sampling strategies, uncertainty estimation, methodological choice based on identification of key categories (those which make greatest contributions to the absolute level and trend in emissions and removals), quality assurance and quality control (QA/QC), and time series consistency. QA/QC entails amongst other things internal self-consistency checks, and may include checks against independent, or at least independently-compiled, estimates (Section 2.3.4).

Good practice entails the following general principles:

▸ Transparency (documentation sufficient to assess the extent to which good practice requirements have been met – includes a clear description of input data, methods and assumptions)

▸ Completeness (all relevant categories of emissions and removals are estimated and reported)

▸ Consistency (differences between years reflect differences in emissions or removals and are not artefacts of changes in methodology or data availability)

▸ Comparability (inventory estimates can be compared between countries)

▸ Accuracy (delivered by the use of methods designed to produce neither under- nor over-estimates and reduces uncertainties so far as practicable – this addresses both accuracy and precision)

The REDD+ MRV decision 14/CP.19 refers to these terms except *comparability*, and in the REDD+ context *completeness* is used in the sense that the provision of information should allow for reconstruction of the results.

Use of remote sensing data may require special attention to consistency, because satellites go out of commission or operability, new ones enter into use, and ways of using the imagery evolve. This may affect time series of emissions estimates and the consistency with historical data which is necessary for establishing FRELs or FRLs. Generic guidance for maintaining consistency is provided in GPG2003 and the 2006GL[30]. Techniques described in Chapter 5, Section 5.1 should also be applied to minimise bias even if data sources do change over time.

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[29] See section 1.3, GPG2003, or section 3 in the Overview in Vol 1 of the 2006GL

[30] See section 5.6 of the GPG2003 (Time Series Consistency and Methodological Change) or Vol 1, Chapter 5 of the 2006 GL (Time Series Consistency)

Developing countries currently may not have data and estimates that meet these general principles fully. The most common issues, based on those identified in a 2009 technical paper from UNFCCC[31], are:

▸ lack of suitable data for regularly estimating forest area change and changes in forest carbon stocks in many countries. Carbon stock data for above-ground and below-ground pools are often based on estimates or conversions using IPCC default data, and few countries are able to provide information on all five carbon pools or estimates from biomass burning. Consequently inventories are often incomplete.

▸ lack of transparency arising from the reliance on expert opinion, independent assessments or model estimations as information sources to produce forest carbon data in the absence of suitable data national specific data

▸ estimates based either on single-date, sample measurements or on integration heterogeneous data sources, rather than using a systematic and consistent measurement and monitoring approach, thus consistency cannot be ensured

▸ lack of experience in applying the IPCC GPG as a common approach for estimation and monitoring

▸ limited information on sources of error and uncertainty levels of the estimates provided by countries, and on approaches to analysing, reducing, and dealing with these in international reporting.

Despite significant (though not necessarily even) progress since 2009, these issues still need consideration. The joint use of remotely-sensed and ground-based data as outlined in the MGD can help address these issues, in the context of REDD+ activities.

2.2.2   GHGI coverage, approaches, methods and tiers

For reasons of transparency and consistency (as requested by COP decisions 12/CP.17, 11/CP.19 and 13/CP.19), countries should where possible use the same approaches, methods and data for reporting forestry emissions in national greenhouse gas inventories (GHGI) and REDD+ reports. However there reasons why GHGI and REDD+ may not be straightforward to compare; e.g. GHGI estimates contain national estimates of emissions and removals from land use and land use change, whilst REDD+ estimates are for activities which may be sub-national as an intermediate step, and in some cases may have different data and methods because the REDD+ and GHGI estimates may not yet be fully aligned. It is important to ensure consistency where possible, document any differences, and to understand and communicate implications where differences may occur. The relationship between REDD+ estimates and GHGIs in the context of FREL and FRLs is discussed further in Section 2.3.3.

GPG2003 provides methodologies to estimate changes in five carbon pools (above-ground biomass, below-ground biomass, dead wood, litter, and soil organic matter[32]) and non-CO_2 GHG emissions for six categories of land use (Forest Land, Cropland, Grassland, Wetland, Settlements and Other Land), and for changes between land uses. Table 2: Definitions for carbon pools and Table 3: IPCC top-level

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[31] UNFCCC 2009 Technical paper FCCC/TP/2009/1 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.

[32] The GPG2003 also provides three alternative methods for dealing with harvested wood products.

land categories for greenhouse gas (GHG) inventory reporting show how IPCC defines these pools and land categories.

Table 2: Definitions for carbon pools

Pool		Description
Biomass	**Above-ground biomass**	All living biomass (expressed in tonnes dry weight) above the soil including stem, stump, branches, bark, seeds, and foliage. Note: In cases where forest understorey is a relatively small component of the aboveground biomass carbon pool, it is acceptable for the methodologies and associated data used in some tiers to exclude it, provided the tiers are used in a consistent manner throughout the inventory time series.
	Below-ground biomass	All living biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.
Dead organic matter	**Dead wood**	Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country.
	Litter	Includes all non-living biomass with a diameter less than a minimum diameter chosen by the country (for example 10 cm), lying dead, in various states of decomposition above the mineral or organic soil. This includes the litter, fumic, and humic layers. Live fine roots (of less than the suggested diameter limit for below-ground biomass) are included in litter where they cannot be distinguished from it empirically.
Soils	**Soil organic matter**	Includes organic carbon in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series. Live fine roots (of less than the suggested diameter limit for below-ground biomass) are included with soil organic matter where they cannot be distinguished from it empirically.

Adapted from Table 3.1.2, GPG2003[33].

Notes: National circumstances may necessitate slight modifications to the pool definitions. Where modified definitions are used, it is good practice to report upon them clearly, to ensure that modified definitions are used consistently over time, and to demonstrate that pools are neither omitted nor double counted.

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[33] Table 1.1, vol 4, section 1.3 contains the corresponding carbon pool definitions used in the 2006 Guidelines

Table 3: IPCC top-level land categories for greenhouse gas (GHG) inventory reporting

IPCC Land Category[34]	Description
Forest Land	This category includes all land with woody vegetation consistent with thresholds used to define Forest Land in the national GHG inventory, sub-divided into managed and unmanaged, and also by ecosystem type as specified in the *IPCC Guidelines*[35]. It also includes systems with vegetation that currently fall below, but are expected to exceed, the threshold of the Forest Land category.
Cropland	This category includes arable and tillage land, and agro-forestry systems where vegetation falls below the thresholds used for the Forest Land category, consistent with the selection of national definitions.
Grassland	This category includes rangelands and pasture land that is not considered as Cropland. It also includes systems with vegetation that fall below the threshold used in the Forest Land category and which are not expected to exceed, without human intervention, the threshold used in the Forest Land category. The category also includes all Grassland from wild lands to recreational areas as well as agricultural and silvopastural systems, subdivided into managed and unmanaged consistent with national definitions.
Wetlands	This category includes land that is covered or saturated by water for all or part of the year (e.g., peatland) and that does not fall into the Forest Land, Cropland, Grassland or Settlements categories. The category can be subdivided into managed and unmanaged according to national definitions. It includes reservoirs as a managed sub-division and natural rivers and lakes as unmanaged sub-divisions.
Settlements	This category includes all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with the selection of national definitions.
Other land	This category includes bare soil, rock, ice, and all unmanaged land areas that do not fall into any of the other five categories. It allows the total of identified land areas to match the national area, where data are available.

IPCC provides methods to estimate emissions for land remaining in a given category, and for land converted from one category to another. Table 4: Land use conversion and definitions according to IPCC good practice shows the possible conversions and the codes used conventionally for them. Land is conventionally assumed to remain in *a land converted* category for 20 years after the transition that took it to a new land use. This assumption can be relaxed at Tier 3 (Box 6: The IPCC tier concept)[36].

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section 2.2 in the GPG2003

[35] The forest ecosystem types referred to are, for tropical ecosystems: wet; moist with short dry season; moist with long dry season; dry; montane moist; montane dry.

[36] GPG2003 section 3.2 states 'Lands that have been converted to another land use should be tracked under the appropriate sections for as long as carbon dynamics are influenced by the conversion and follow up dynamics.

Table 4: Land use conversion and definitions according to IPCC good practice

Land Remaining Categories	Land Converted Categories
FF = Forest Land Remaining Forest Land	LF = Land Converted to Forest Land
CC = Cropland Remaining Cropland	LC = Land Converted to Cropland
GG = Grassland Remaining Grassland	LG = Land Converted to Grassland
WW = Wetlands Remaining Wetlands	LW = Land Converted to Wetlands
SS = Settlements Remaining Settlements	LS = Land Converted to Settlements
OO = Other Land Remaining Other Land	LO = Land Converted to Other Land

Deforestation is estimated as the sum of emissions and removals associated with conversions from forest to other land uses. Removals are possible because of growth of biomass in the post-deforestation land use (i.e. cropland, grassland) following conversion. Neither GPG2003 nor the 2006GL identifies forest degradation, conservation of forest carbon stocks, and sustainable management of forests by name, but these can be estimated as the effect on emissions and removals of human interventions on land continuing to be used as forests[37]. Enhancement of forest carbon stocks may occur within existing forests and also include the effect of conversion from other land uses to forest. How to make these estimates, including cross referencing the methods described by IPCC is described in Chapter 3, Section 3.1. Box 5: Land use and REDD+ activities summarizes how REDD+ activities and IPCC land use categories relate to each other.

IPCC describes three approaches to providing activity data involving land area[38]. Approach 1 is not spatially explicit[39] and simply uses net areas associated with land use. Approach 2 provides the matrix of changes between land uses. Approach 3 is geographically explicit and allows tracking of land use changes over time and is suited to situations where land use is dynamic, with multiple changes in cover or use over time. Remote sensing data are likely to be used to greatest advantage with Approaches 2 and 3.

Spatial stratification based on type or extent of human activities or type of forest should improve the quality of the results whatever the tier. For example, forests may be subdivided by using data on ecosystem type, climate, elevation, disturbance history, and/or management practice. More information on stratification is provided in Section 2.3.2. IPCC methods are applied at the level of the different carbon pools within the strata and the emissions and removals summed.

IPCC describes methods at three levels of detail, called *tiers*. Box 6: The IPCC tier concept summarizes the definition of Tiers, based on the description in the GPG2003. Tier 1 is also called the *default method*, and the IPCC guidelines aim to provide the information needed for any country to implement Tier 1, including emission and removal factors and guidance on how to acquire activity data. Tier 2 usually uses the same mathematical structure as Tier 1 with countries providing data specific to their national

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20 years is consistent with IPCC Guidelines, but Tier 3 methods may use longer periods where appropriate to national circumstances.

[37] In IPCC terms, forest land remaining forest land.

[38] See Chapter 2 of the GPG2003, or Vol 4, Chapter 3 of the 2006GL

[39] Spatially explicit means having a location that can be identified on the ground using geographical coordinates and applies to both individual sampling sites and exhaustive tessellations obtained from wall-to-wall remotely sensed data.

circumstances. This would typically require field work to estimate the values required if they do not exist. Tier 3 methods are generally more complex, normally involving modelling and higher resolution land use and land-use change data. IPCC expects that higher Tier (meaning Tier 2 or Tier 3) methods will be applied for *key categories* (Section 2.2.3), unless the data collection to do this would significantly jeopardize resources required for other key categories[40].

Experience of developing national GHG emissions estimates suggests that even a system that is Tier 3 overall will use Tier 1 or Tier 2 emissions/removals factors for some components. For example, all operating Tier 3 systems calculate carbon dioxide and methane emissions from fire using models, but typically use emissions/removals factors to estimate the nitrous oxide emissions associated with wildfires and slash burning (Kurz et al., 2009). Some Tier 3 systems use Tier 1 or 2 methods for on-going emissions of soil carbon following deforestation. For national GHG reporting, a combination of tiers, most often Tier 1 and Tier 2 may be used, and any combination of Tiers and Approaches, as described above. For REDD+, Approach 3 could provide the spatially explicit information needed to track activities and drivers, and to support estimation of GHG emissions or removals. Increased availability of remotely sensed data makes this more practicable. This may have consequences for national GHGI development, so consistency between the two can be established.

The selection of the appropriate Tier and Approach to use for GHG estimation and for other purposes depends on country circumstances including system development and operational budgets, infrastructure and capacity as well as intended use of outputs from the system. A summary of the key factors to consider is provided in the form of a decision-tree in Figure 2: Key factors relevant to system design, tier and approach selection in GHG estimation. Cost-effectiveness is discussed in 1 and Appendix A.

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[40] See fig 5.4.2 in GPG2003, Decision tree to choose a good practice method

Figure 2: Key factors relevant to system design, tier and approach selection in GHG estimation
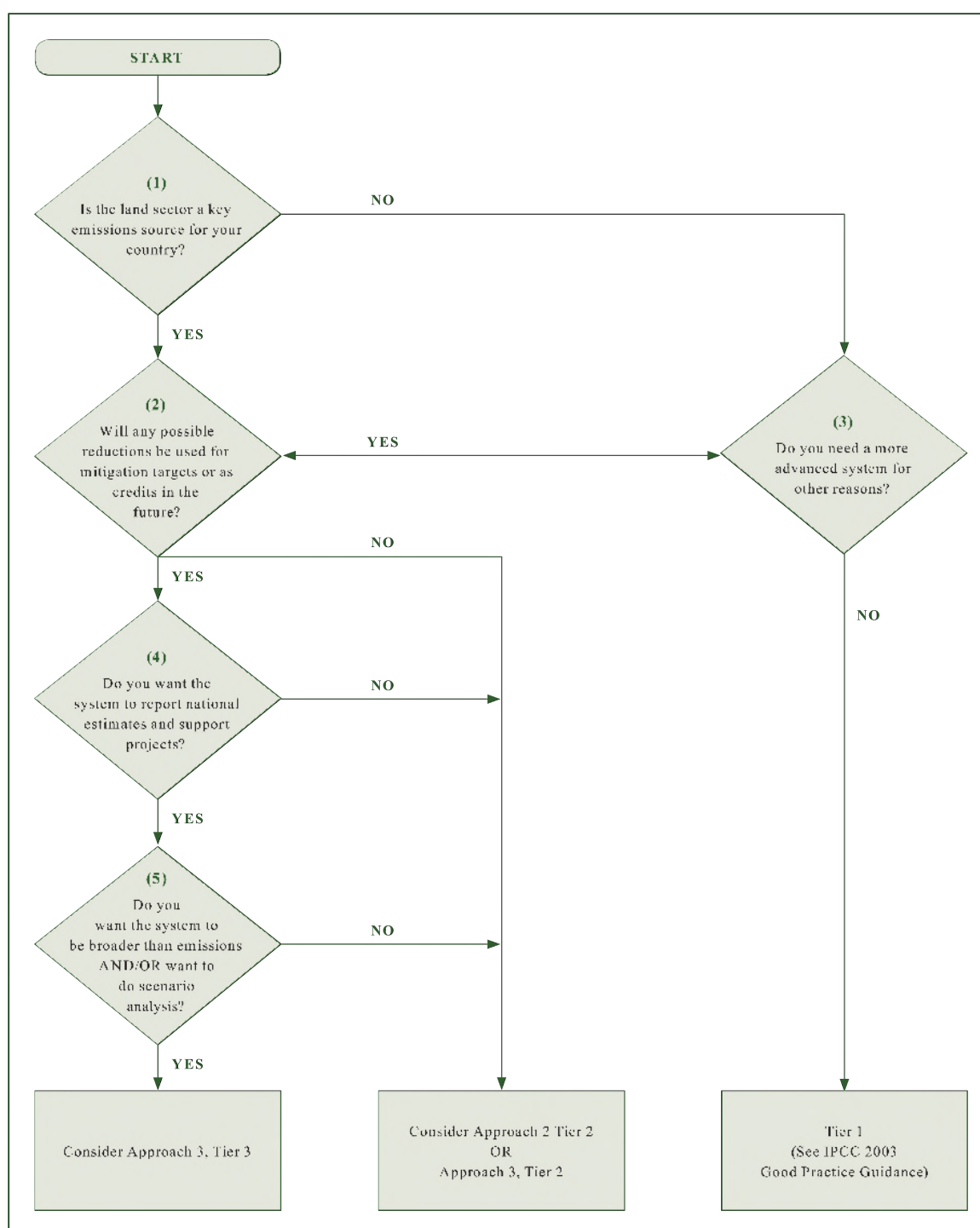
Considerations at the decision points in the tree are as follows:

Decision Point 1: Is the land sector a key emissions source for your country?

Whether the land sector is a key category will depend on the proportion of emissions that the land sector emits (see key category analysis, Section 2.2.3). It is possible to test if the land sector is going to be a key sector using Tier 1 methods, in the absence of national data (see GPG2003).

Decision Point 2: Will any possible reductions be used for mitigation targets or results based payments?

A more advanced system than Tier 1 is likely to be required to support mitigation targets for results based payments.

Decision Point 3:Do you need a more advanced system for other reasons?

There are reasons other than UNFCCC reporting to develop a MRV system (e.g. monitoring and reporting on forest resource assessment or more broadly national environmental performance). If the land sector is not a key category in the national greenhouse gas inventory and you do not need an MRV system for other reporting purposes then apply Tier 1.

Decision Point 4: Do you want the system to report national estimates and support projects?

Sub-national and project level reporting should demonstrate consistency with national estimates and document how data acquisitions and calculations are conducted in support of each other.

Decision Point 5: Do you want the system to be broader than emissions?

Some examples of broader requirements (other than those specified in Note 3) include: consideration of including wider land sector activities; environmental and social safeguards; land use planning etc.

Decision Point 6: Do you want to do scenario analysis?

Scenario analysis can be useful in understanding and predicting impacts of various mitigation actions on future results based payments.

IPCC distinguishes between two methods for estimating emissions and removals of CO_2 associated with annual rates of change in all carbon pools[41]. These are the gain-loss method (which estimates annual emissions and/or removals separately and directly), and the stock change[42] method (which estimates net annual emissions or removals from the difference in total carbon stocks at two points in time divided by the number of intervening years). Considerations for selecting and applying these methods are discussed below. The carbon stock estimates for the stock change method are commonly estimated from repeated field measurements of forest variables as part of an NFI (Chapter 4, Section 4.2.1) or equivalent survey data. Remote-sensing data may be useful in improving the efficiency of sampling in an NFI by assisting in stratification[43] and by providing auxiliary data during estimation.

IPCC notes that the stock change method provides good results where there are relatively large increases or decreases in estimated biomass, or where there are statistically rigorous NFIs [44]. Since countries may not possess an NFI[45], and NFIs by themselves do not track or map REDD+ activities, the advice in the MGD focuses more on the gain-loss method. The gain-loss method requires ground data which can come from an NFI as discussed in Chapter 4, Section 4.2.1.

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[41] For the gain-loss method see equation 3.1.1 in the GPG2003 or equation 2.7 in volume 4 of the 2006 GL. For the stock change method see equation 3.1.2 in the GPG2003 or equation 2.8 in volume 4 of the 2006GL.

[42] The stock-change method is called the stock difference method in the 2006GL.

[43] See Section 2.3.2 on stratification.

[44] See page 3.25 of the GPG2003, or page 2.13 in Volume 4 of the 2006 GL.

[45] Or may not possess an NFI with suitable statistical design

The gain-loss method estimates annual net emissions or removals of CO_2 as the sum of gains and losses in carbon pools occurring on areas of land subject to human activities. This may be achieved by the use of emissions/removals factors and activity data or by the use of more sophisticated representative models and integrated systems as discussed briefly at the end of this section and in more detail in 3. Most of what follows relates to use of emissions/removals factors and activity whereby changes in the carbon pools are estimated as the product of an area of land and an emission or removal factor that describes the rate of gain or loss in each carbon pool per unit of land area.

To estimate emissions and removals using this method, countries need *activity data*, i.e. information about the extent of REDD+ activities[46]. Remote-sensing is likely to provide the main source.

Activity data combined with emission and removal factors and other parameters, usually expressed per unit area, are used to estimate emissions or removals. Activity data generally correspond to strata based on forest type and condition, management practice or disturbance history. Stratification may require auxiliary data and is useful in increasing accuracy and in linking to appropriate emission and removal factors.

For conversions from forest to other land uses which are summed to estimate total deforestation, the gain-loss method multiplies areas of land-use change by the difference in carbon stocks per unit area between forest and the new land use. For Forest Land remaining Forest Land, the gain-loss method estimates the annual change in above-ground biomass carbon as the difference between the annual increment in carbon stocks due to growth and the annual decrease in stocks due to losses from processes such as commercial harvest, fuel wood removal[47], and other disturbances such as fire and pest infestation (Chapter 3.2 in GPG2003; Cienciala et al., 2008). Collation of data on gains and losses may be useful in management and policy scenario analysis. The balance of gains and losses (i.e. net change) can also be estimated from sample plots representative of strata subject to the processes involved.

The choice between using a gain-loss or stock change method at the appropriate Tier[48] will depend on expert judgment, taking the status of national inventory systems and forest characteristics into account. Figure 3: Method selection for estimating CO_2 emissions and removals based on available data summarizes these choices recognising that, even if not used directly for estimating emissions and removals associated with REDD+ activities, an NFI, where it exists, can provide potentially useful data for use with the gain-loss method, so that the approaches are in a sense complementary. This is discussed further in Chapter 4, Section 4.2.2.

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[46] REDD+ activities are identified in paragraph 70 of decision 1/CP.16

[47] Other auxiliary data such as log input to processing plant together with an estimate of intermediate losses may also be relevant see Chapter 4, Section 4.2.3 or more detail.

[48] Because of the data requirements the stock change method is not appropriate at Tier 1.

Figure 3: Method selection for estimating CO$_2$ emissions and removals based on available data
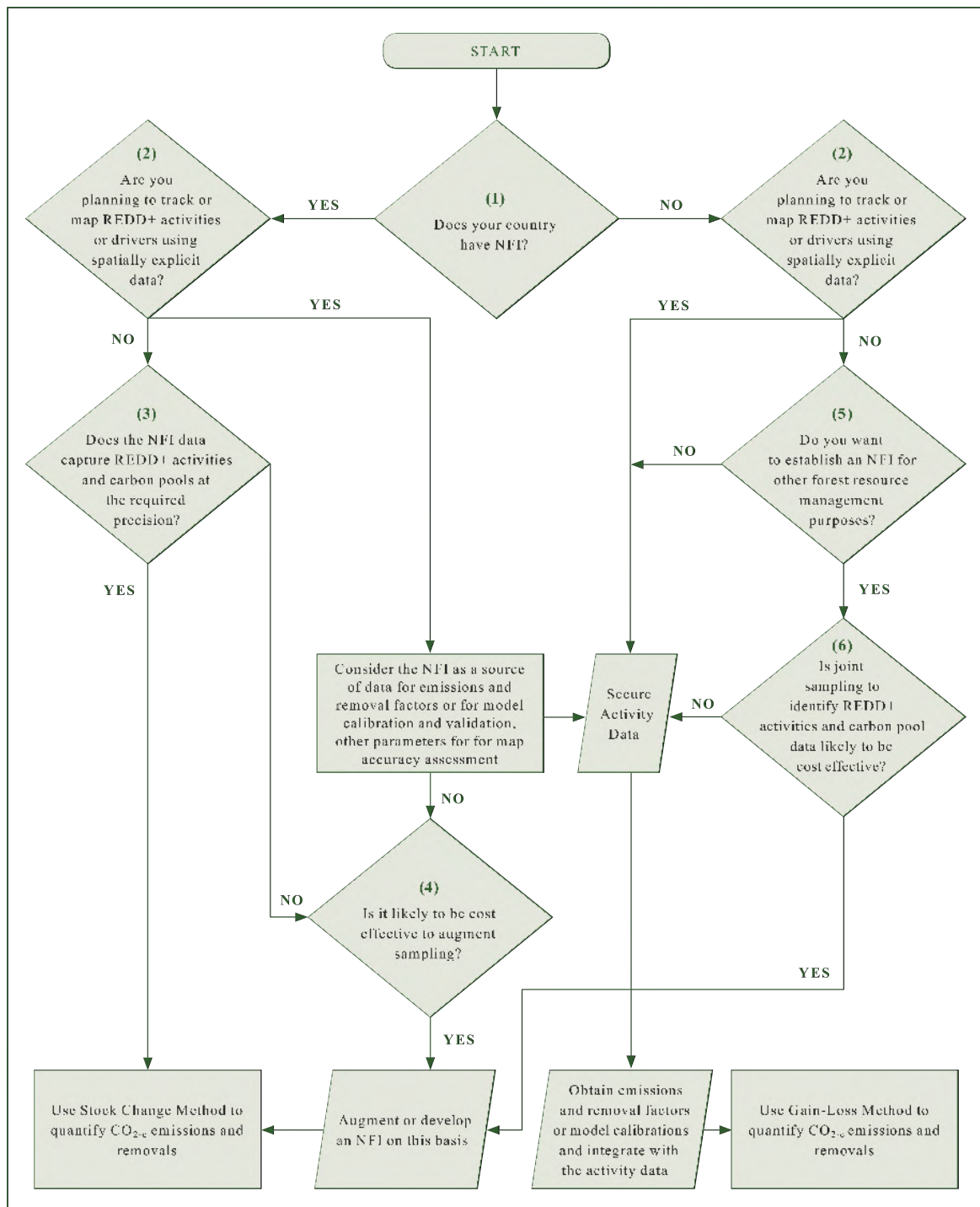
Considerations at the decision points in the tree are as follows:

Decision Point 1: Does you country have a National Forest Inventory (NFI)?

An NFI is a periodically updated sample-based system covering all forests within a country to provide information on the state of a country's forest resources. Where NFI data have been collected on a consistent basis for more than one point in time this data can be used to directly estimate carbon stock change between two points in time and can be used to estimate emission and removal factors.

Decision Point 2: Are you planning to track or map REDD+ activities or drivers using spatially explicit data?

Mapping using spatially explicit data is useful for understanding the relationship between REDD+ activities and drivers, e.g. for policy analysis.

Decision Point 3: Does the NFI data capture REDD+ activities and carbon pools at the required precision?

Existing NFI sampling designs are unlikely to be optimized to estimate REDD+ activities such as deforestation or forest degradation, or carbon pools within the areas subject to land use change, leading to increases in uncertainties in estimating emissions and removals. Key category analysis will assist in assessing if the NFI data is capturing REDD+ activities and carbon pools at the required precision.

Decision Point 4: Is it likely to be cost effective to augment sampling?

Adding to the sampling may be required where required precision is not achieved. Although an NFI for an entire country might be desirable, it is often logistically complex and expensive in large countries, especially those with large areas of non-commercial forest. Increasing the sample size could be regarded as cost effective if it saved resources relative to alternative approaches, or did not involve disproportionate additional expenditure given the benefit anticipated.

Decision Point 5: Do you want to establish an NFI for other forest resource management purposes?

The broader national benefits to be realised from an NFI should be considered in the assessment of cost effectiveness and other broader decision making.

Decision Point 6: Is joint sampling to identify REDD+ activities and carbon pool data likely to be cost effective?

A step could be regarded as cost effective if it saved resources relative to alternative approaches, or did not involve disproportionate additional expenditure given the benefit anticipated.

The gain-loss method can be implemented using default emission/removal factor data from IPCC guidelines and guidance (Tier 1), or nationally relevant data from sampling, forest inventories or research sites (Tiers 2 or 3). Emissions/removals factors do not necessarily represent any specific point on the ground, but are applied to various strata. Emissions/removals factors can be applied at a single point in time (for example, biomass loss during a deforestation event) or over longer periods to represent ongoing gain or loss of carbon (e.g. ongoing loss of soil carbon, or gain of carbon by regrowth of forests). Emissions/removals factors should be representative of the spatial and temporal scale at which they are applied. Use of emissions/removals factors may represent an interim step towards Tier 3 systems, which are more complex but, properly implemented, offer advantages of better representation of the relationships between pools, and greater spatial detail (Chapter 3, Section 3.2).

Box 5: Land use and REDD+ activities

The Cancun Agreements identify five REDD+ *activities*, namely (a) reducing emissions from deforestation; (b) reducing emissions from forest degradation; (c) conservation of forest carbon stocks; (d) sustainable management of forests; (e) enhancement of forest carbon stocks. The IPCC 2003 GPG refers to five land *uses,* namely forest land, cropland, grassland, wetlands, settlements and other land. The relationship between the REDD+ activities and IPCC land uses is as follows:

▸ Deforestation is an activity that converts forest land to other land uses

▸ Degradation, conservation of forest carbon stocks, and sustainable management of forests are activities that occur within forest land that is not converted to other land uses, but remains forest land

▸ Enhancement of forest carbon stocks can occur either by converting other land uses to forest land, or within forest land that remains as forest land.

GPG2003 regards deforestation as the sum of conversions from forest land to other land uses. As a default assumption when land is converted to another land use it remains in the land conversion category for 20 years. Therefore as a default assumption deforestation estimates should represent the sum of emissions that occur in the year of conversion of forest to another land use, and any lagged emissions or removals (e.g. due to change in soil carbon or regrowth of biomass on the subsequent non-forest land use) for 20 years thereafter. This is consistent with the advice provided in Chapter 3, Section 3.1.1 below.

When a REDD+ activity converts land to forest (e.g. through planting of trees on cleared land that results in enhancement of forest carbon stocks) so long as the forest created remains as forest the simplest procedure is to continue to consider over time that land as part of the original REDD+ category, rather than to later transfer to another category (e.g. sustainable management of forests). This is because i) if the land remains forest there is no subsequent land use change to worry about, and ii) countries may not in fact have selected another REDD+ activity to which the created forest could be transferred.

Countries may wish to depart from the above approach for three reasons. Firstly (and consistent with a stepwise approach) countries may not yet have the capacity to track non-forest land use. In this case if the estimates are based just on the year of conversion they will omit subsequent removals from regrowth or emissions from loss of soil carbon. As tracking capacity improves it should be possible to include lagged emissions and removals. Secondly in the case of conversion of forest that was growing on organic soils that are subsequently drained, countries may wish to continue to count these as deforestation emissions while the drainage continues, even beyond the 20 year period. Thirdly countries may wish at some point to reassign land to various REDD+ activities, probably resulting from changes in methodology or policy. In all cases countries should ensure that the REDD+ emission and removals estimates and the estimation of the FREL and/or FRL use the same methods (Chapter 3). For countries tracking lands and/or making transitions to full land use accounting, reporting challenges will become more obvious as they draw on denser and longer time series of land use change data. Neither the UNFCCC REDD+ decisions, nor GPG2003 describes how to allocate lands and emissions/removals for REDD+ activities in circumstances where there are (multiple) land use (or REDD+ activity) changes through time, but general to avoid double counting and omission of emissions and removals for countries tracking land uses the MGD advice is to:

▸ where necessary, develop sub-categories under the relevant IPCC land use classes to allow transparent and consistent reporting where lands under REDD+ activities differ from IPCC land use categories

▸ establish and document reporting rules that describe under which land uses emissions and removals will be reported.

Countries should ensure that tracking of lands between IPCC land uses and/or REDD+ activities does not lead bias estimates of emissions or removals, e.g. by selective inclusion. Further advice on full tracking of lands and events which lead to multiple changes in land use or REDD+ activity through time is provided in Chapter 3, Section 3.2.

See GPG2003 page 3.23 and 2006GL vol 4, section 4.2 and 4.3

Box 6: The IPCC tier concept

The IPCC classifies the methodological approaches in three different Tiers, according to the quantity of information required, and the degree of analytical complexity (IPCC, 2003, 2006).

Tier 1 employs the method described in the IPCC Guidelines using country specific activity data and the default emission/removal factors and other parameters provided by the IPCC. There are simplifying assumptions about some carbon pools (e.g. dead wood and litter pools may be combined as 'dead organic matter' and dead organic matter stocks are assumed to be steady for non-forest land use categories; though, for Forest Land converted to another land use, default values for estimating dead organic matter carbon stocks are provided). Tier 1 methodologies may be combined with spatially explicit activity data estimated from remote sensing. The stock change method is not applicable at Tier 1 because of data requirements (GPG2003).

Tier 2 generally uses the same methodological approach as Tier 1 but applies emission/removal factors and other parameters which are specific to the country. Country-specific emission/removal factors and parameters are those more appropriate to the forests, climatic regions and land use systems in that country and all five pools are covered explicitly. More highly stratified activity data may be needed in Tier 2 to correspond with country-specific emission/removal factors and parameters for specific regions and specialised land-use categories.

At Tier 3, higher-order methods include models and can utilize data from national ground monitoring programmes to address national circumstances. Tier 3 systems are generally more flexible than Tier 1 or 2 systems as they can more easily accommodate a wide range of different disturbance events. Properly implemented, these methods can provide estimates of greater certainty than lower tiers, and can have a closer link between biomass and soil carbon dynamics. Such systems may be GIS-based combinations of forest type and age class/production systems with connections to soil modules, integration several types and sources of data. Combined with Approach 3 they can provide accurate estimates of carbon stock changes and associated emissions and removals for changes in land use or management over time. These systems may include a climate dependency, and provide estimates with inter-annual variability.

Progressing from Tier 1 to Tier 3 generally represents a reduction in the uncertainty of GHG estimates, though at a cost of an increase in the complexity of measurement processes and analyses. Lower Tier methods may be combined with higher Tiers for pools which are less significant. There is no need to progress through each Tier to reach Tier 3. It may be simpler and more cost-effective to transition from Tier 1 to 3 directly than produce a Tier 2 system that then needs to be replaced. For example, where detailed forest inventory data is available it may be possible to develop empirical growth curves from these data almost as easily as developing emissions/removals factors (see Box 11: Mass Balance Approaches and example of the CBM-CFS3).

2.2.3   Significance and key category analysis

Key category analysis (KCA) is IPCC's method for deciding which emissions or removals categories to prioritize in preparation of the GHGI. A category is *key* if, when categories are ordered by magnitude, it is one of the categories contributing cumulatively to 95% of total national emissions or removals, or to 95% cumulatively of the trend in national emissions or removals. KCA is described and in section 5.4 of GPG2003, and volume 1, Chapter 4 of the 2006GL. Since it is not known at the outset which categories are key, KCA may need to be iterative with the initial ordering undertaken using Tier 1 methods.

REDD+ activities are mostly not recognised categories in the IPCC inventory methodology, but in the case of deforestation, GPG2003 suggests adding up the forest to other land use conversions that contribute to deforestation, and treating deforestation as key if the result is larger than the smallest category considered to be key using the UNFCCC reporting categories. IPCC also provides qualitative criteria for identifying key categories, one of which is that categories for which emissions are being reduced, or removals enhanced, should be treated as key. To the extent that this qualitative criterion applies in the case of REDD+ activities, they could be treated as key, although there has been no COP decision on this.

In applying KCA[49], GPG2003 asks whether particular subcategories defined for this purpose are *significant*. The subcategories defined for these purposes are for CO_2 are biomass, dead organic matter and soils[50]. For IPCC, significant subcategories are those which contribute at least 25% to 30% of the emissions or removals in the parent category to which they belong. This does not mean that sub-categories may be omitted, but for subcategories which are not significant in this sense, countries may use Tier 1 methods if country specific data are not available. Identifying key subcategories assists in the allocation of resources to collect country specific data and in addition focuses efforts to reduce uncertainties related to these key subcategories.

Decisions 12/CP.17 and 13/CP.19 say that significant pools and activities should be included in FREL and/or FRLs, and that Parties have some flexibility not to include other pools and activities, considered not to be significant. For reasons of consistency, it is clear that inclusion of pools and activities should be the same in the FREL and/or FRL as for the subsequent emissions and removals estimates from REDD+ activities.

Drawing on a precedent from IPCC usage, significant pools could be taken to be those accounting for 25% to 30% or more of the GHG emissions or removals associated with a REDD+ activity[51]. The analogy is not exact because IPCC uses the 25% to 30% level to define as significant pools for which default methodologies can be applied, even if the parent category to which they belong is a key category. This is not the same as deciding on potential omission of a pool consistent with decision 12/CP.17 and 13/CP.19. Another possible (though not necessarily mutually exclusive) way to approach significance, based on a set of rules to help ensure a consistent policy signal, that achievement in emissions reductions

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[49] As set out in section 3.1.6 of GPG2003 the decision trees provided by GPG2003

[50] See table 3.1.3, page 3.20 of GPG2003. For N_2O the subcategories used for KCA are fire, soil organic matter mineralisation, nitrogen inputs and cultivation of organic soils. For CH_4 the subcategory is fire.

[51] Other percentage levels could be used to define *significant* are possible; e.g. the FCPF Methodological Framework uses 10%.

or removals enhancement would not be overestimated and to prioritize the most relevant sources. For example:

▸ the pool likely to be responsible for the largest cumulative emissions addressed by the REDD+ activity (or removals if the carbon stocks addressed by the activity are increasing) is the most significant.

▸ other pools not already included can potentially be considered not significant if they behave in the same direction as the most significant pool (i.e. their carbon stocks increase or decrease when those from the most significant pool increase or decrease, respectively).

▸ on the other hand, pools expected to behave differently compared with the most significant pool are considered potentially significant, for inclusion at the same time as the most significant pool, or for prioritization in a stepwise approach as better data become available.

For deforestation in tropical biomes, the most significant pool will often be biomass, except where forests are growing on organic soils. In the case of other activities, biomass could be regarded initially as the most significant pool and the other pools tested against this working hypothesis using IPCC methods summarized in the MGD, implemented at Tier 1 for test purposes. As an example, where covered by national forest definitions, for planted forests established on drained organic soils, soil organic carbon is very likely to be significant under the rules suggested above because the pool decreases as biomass increases. The expectation would be to include significant pools using country specific data (hence Tier 2), as these become available. Significance can be kept under review as national monitoring systems develop.

As with pools, for activities a possible consideration could be that the REDD+ activity likely to be responsible for the largest GHG emissions or removals be considered the most significant. Activities unlikely to be affected by displacement (causing greater emissions and/or reduced removals) due to action on the most significant activity could be considered not significant relative to the most significant activity. Activities likely to be affected by displacement due to action on the most significant activity would be considered potentially significant, for inclusion at the same time as the most significant activity, or for prioritization in a stepwise approach as better data become available. Evidence for displacement [52] would include consideration of how action on the most significant activity would affect the drivers of other activities, and hence the emissions and/or removals associated with them. The relationship to proxies may be relevant. Subsequent steps would also allow inclusion of the next largest activities whether or not affected by displacement from activities already included as significant. This process could continue until all activities justified as significant by the Party and considered under the technical assessment process were included.

The relative importance of emissions or removals associated with REDD+ activities may change over time (because of actions taken, evolution of drivers, newly acquired data or improved methods), so significance, where applied, should be reassessed periodically, e.g. as part of a stepwise approach, and in particular when assessing results.

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[52] Noting that, according to decision 9/CP.19, paragraph 4, countries should provide the most recent summary of information on how all of the safeguards (as referred to in decision 1/CP.16, appendix I, paragraph 2), including actions to reduce displacement of emissions, have been addressed and respected before they can receive results-based payments.

2.3   Design decisions relevant to national forest monitoring systems

NFMS are established by countries for forest monitoring. Their characteristics in the context of REDD+ activities are described in decisions 4/CP.15 and 11/CP.19. They should build on existing systems and provide data that are transparent and consistent over time and suitable for MRV. NFMS functions may therefore include data collection, analysis and archiving. NFMS functions will depend on national circumstances, and also could include working with national policy makers to help decide the REDD+ activities under consideration, the associated data requirements, identifying existing data and any data acquisition needs. The MGD assumes that NFMS would include engagement with a range of stakeholders including national authorities with responsibilities for forest land[53], agencies responsible for collecting national data such as the NFI, census information, agencies responsible for estimating forest-related emissions and removals for the national GHGI, and possibly stakeholder representatives including community representatives and the private sector. In performing their functions, NFMS are likely to address some or all of the design decisions covered in the following sections.

2.3.1   Definition of forest

A forest definition[54] is needed to be able to determine whether deforestation or afforestation or reforestation has taken place, and to define the areas within which degradation and the other REDD+ activities may occur. Definitions can have a significant effect on the estimate of emissions or removals associated with REDD+ activities, and the allocation to each activity. Definitions should be used consistently over time and across REDD+ activities, and the definition used to establish the FREL or FRL should be the same as that used subsequently for MRV. For example exclusions from the forest definition, e.g. for oil palm plantations, should be applied consistently over time.

No single definition of forest has been agreed under the UNFCCC for REDD+ purposes. The annex to decision 12/CP.17 requests Parties to provide the definition of forest used, and if it differs from the definition of forest used in the national GHGI, or in reporting to other international organizations, to explain why, and why the definition used in the construction of FREL and/or FRL was chosen. This indicates an expectation that the forest definition used for REDD+ will be the same as that used for previous reporting on forests or that other reporting will be updated to reflect any new definition.

In considering forest definitions, NFMS may wish to note that, as already identified in Table 3: IPCC top-level land categories for greenhouse gas (GHG) inventory reporting, the GPG2003 defines Forest Land as including *all land with woody vegetation consistent with thresholds used to define forest land in the national GHG inventory, sub-divided into managed and unmanaged, and also by ecosystem type as specified in the IPCC Guidelines. It also includes systems with vegetation that currently fall below, but are expected to exceed, the threshold of the forest land category*. The Forest Land definition in the 2006GL refers to *threshold values*. IPCC therefore anticipates that countries will have a forest definition with quantitative thresholds, based on land use since temporary loss of forest cover does not entail transition to another land use provided there is expectation of recovery of threshold values. Threshold values commonly refer to minimum area, percentage crown cover and tree height although other thresholds are possible e.g. referring to minimum width.

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[53] Such agencies could include those responsible for Forestry, Agriculture, and Environment.

[54] A general discussion of forest definitions is provided by Tomppo et al. 2010. National Forest Inventories: Pathways to common reporting. Springer.

The IPCC definition subdivides forests into managed and unmanaged. This is because anthropogenic carbon stock changes and associated greenhouse gas emissions and removals are assumed[55] to occur predominantly on managed land and therefore those on land remaining unmanaged are not reported under the IPCC Guidelines. Reporting is required when unmanaged land is subject to land use conversion[56]. According to GPG2003, *Managed land may be distinguished from that unmanaged by fulfilling not only the production but also ecological and social functions. The detailed definitions and the national approach to distinguishing between unmanaged and managed land should be described in a transparent manner*[57]. Given this broad definition of 'managed' it is entirely possible that countries may have little or no land considered unmanaged.

The detailed definition of what is considered managed may differ from country to country, but national definitions should be applied consistently over time otherwise there is risk that apparent changes in emissions or removals will reflect differences in the way definitions are applied, rather than the effect of REDD+ activities. For the same reason the procedures used to assess whether thresholds are met also need to be applied consistently over time, especially where different methods (e.g. ground-based and remote sensing) are being used together. How consistency is achieved could usefully be reported under MRV provisions. Issues include determination of forest boundaries in fragmented landscapes (relevant to minimum area), determination of crown cover[58], and how height is determined, or (where used as a criterion) minimum width.

Countries that do not already have a forest definition may wish to note that for Kyoto Protocol (KP) purposes Forest *…is a minimum area of land of 0.05–1.0 hectare with tree crown cover (or equivalent stocking level) of more than 10–30 per cent with trees with the potential to reach a minimum height of 2–5 metres at maturity. 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 per cent or tree height of 2–5 metres are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest*[59].

The Cancun Agreements specify that REDD+ mitigation actions should not incentivize conversion of natural forests and therefore the NFMS should be able to distinguish natural forest within land meeting the forest definition. This may require supplementary data on the distribution of forest ecosystems within the country.

National forest definitions need to support reliable classification of forest areas and changes, and hence to estimate carbon stock changes, and associated GHG emissions and removals. In establishing a national

[55] See discussion in 2006GL vol 4 page 1.5

[56] GPG2003 Chapter 2, page 2.5

[57] The 2006 GL say that *Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions. All land definitions and classifications should be specified at the national level, described in a transparent manner, and be applied consistently over time.*

[58] See e.g. Magdon P & C Kleinn 2012. Uncertainties of forest area estimates caused by the minimum crown cover monitoring. Environment Monitoring and Assessment 185(6): 5345-5360.

[59] In the Forest Resource Assessment 2010 FAO defines Forest as Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. The area threshold falls within the range in the KP definition and the height threshold is at the upper end of the KP range.

forest definition it is important to distinguish 'forest cover' from 'forest land', which is typically reported by forest inventories and takes account of land-use.

From the forest inventory perspective, and as defined by Food and Agricultural Organization of the United Nations (FAO), forest land may include areas that are temporarily treeless as a result of harvesting or natural disturbance. The same land may be classified as non-forest category by remote-sensing of land cover, and in a forest category from an inventory of forest land. The opposite is also true – the FAO forest definition does not include land that is predominantly agricultural or urban, even if such land has tree cover which may meet the national threshold.

These differences can have a significant effect on the resulting REDD+ estimates and can complicate comparisons with land cover classification approaches, e.g. when losses due to temporary removals of trees followed by regrowth are classified as deforestation according to the national definition, forest land use has been maintained and forest regrowth is expected. This bias can be corrected for by use of auxiliary data, by analysing time series of remotely-sensed data to detect where regrowth is occurring, and by estimating REDD+ activities jointly so that regrowth as well as forest loss is captured. Full tracking of lands affected by REDD+ would require the use of set rules to ensure that lands are correctly categorized and through time.

If in practice information on threshold recovery is not available it may be necessary to base the definition on tree cover, at least until there is sufficient integration of remotely sensed and ground-based data to permit a land-use definition. Clearly the minimum area used in the forest definition can have implications for the spatial resolution of the imagery used to detect forest areas and changes, and may affect the ability to track the identified drivers of changes with different scales, intensity and spatial distribution. Reduction in canopy cover below the minimum does not necessarily entail clearance of the entire area which may require detection at finer resolution, especially with large minimum areas.

Table 5: Forest definitions adopted by countries having submitted FREL/FRLs by February 2016 summarizes the forest definitions used by countries which, by February 2016, had submitted REDD+ reference levels. This table shows that the threshold criteria being used are generally consistent with the forest definition introduced under the UNFCCC for KP purposes. In one case a much larger minimum area unit is used. This was to help capture botanical species and human activity information in a variegated landscape. Its use does not prevent defining forest using smaller minimum areas. The larger the minimum area used, the more land that would otherwise be considered forest will be transferred to other land classifications.

The table also indicates that most countries are not using potential height in their forest definitions adopted for REDD+ purposes. Some countries are excluding various areas that would otherwise meet the forest definition, on the grounds that they are under non-forest land uses. This shows that land use considerations can in fact be used to operationalize the forest definition. In all cases it will be important to apply the forest definition consistently over time and to link it to other definitions in the GHGI to ensure that all significant emissions and removals are reflected in national estimates.

Table 5: Forest definitions adopted by countries having submitted FREL/FRLs by February 2016

Country	Area (ha)	Canopy cover (%)	Height (m)	Exclusions
Brazil (a)	0.5	10	5	Land predominantly under agricultural or urban land use
Chile	0.5	10 / 25	(d)	Self-sown trees of introduced species.

Country	Area (ha)	Canopy cover (%)	Height (m)	Exclusions
Colombia	1	30	5 (e)	Commercial forest plantations, palm crops and planted trees for agricultural production.
Congo	0.5	30	3	--
Costa Rica	1	30	5	--
Ecuador	1	30	5	--
Ethiopia	0.5	20	2	--
Guyana	1	30	5	--
Indonesia (f)	0.25	30	5	Non-natural forested peat
Malaysia	0.5	30	5	Oil palm and rubber plantations
Mexico	50	10	4 (g)	Lands subject to a land use that is predominantly agricultural or urban.
Paraguay	1	10 / 30 (b)	3 / 5 (b)	Urban areas, grasslands, plantations predominantly agricultural, agroforestry and silvopastoral systems, whose primary purpose is agriculture.
Peru	0.09	(c)	5	--
Vietnam	0.5	10	5 (g)	--
Zambia	0.5	10	5	--

Notes: a) Deforestation for the Amazonia biome is not associated with thresholds, but simply with canopy cover equal to zero. Situations in which forest falls below the thresholds of the FAO definition but still does not have canopy cover equals to zero is characterized as forest degradation. b) First alternative applies in the Western region; second in the Eastern c) Detection of forest depends on classification algorithm at the pixel level d) Tree species required to predominate. Minimum width of 40 m applied e) At the time of identification f) Working definition identifies forest through visual interpretation with a polygon size equivalent to 6.25 ha. g) Definition includes the potential to reach this height.

2.3.2   Land cover, land use and stratification

Although the terms land cover and land use may be used interchangeably they are not synonymous. Land cover can change temporarily without change in land use – e.g. tree cover may be temporarily removed but land remains in forest land use if replanting or other regeneration follows.

The GPG2003 ask that the land of a country be reported using the six land use categories previously identified in Table 3: IPCC top-level land categories for greenhouse gas (GHG) inventory reporting, namely Forest Land, Croplands, Grasslands, Wetlands Settlements and Other Land. In general reporting

against the six IPCC land use categories and changes between them cannot be achieved on the basis of remote sensing observations alone but also requires rules for attribution based on spatially explicit location and auxiliary data (Table 6: Examples of auxiliary data and possible assumptions that can help with classifying land use; Chapter 4, Section 4.2.3) e.g. climate, ecosystem, management type, accessibility and time-series analysis (Box 7: Plantation management in Kenya), to distinguish for example whether forest cover loss is due to deforestation (change in land use) or is temporary (no change in land use because tree forest is expected to be replanted of regenerate). This can lead to nationally specific stratification schemes which are then categorized into the IPCC classes according to national definitions.

Attribution is the process of associating observed land-cover changes with underlying causes of disturbance. Knowledge of the cause of disturbance is needed for the estimating GHG emissions and removals because different disturbance types have different impacts on carbon stocks (Kurz et al., 2009).

Table 6: Examples of auxiliary data and possible assumptions that can help with classifying land use

Data	Source	Possible assumption
Forest management plans	Forest agencies, stakeholders	That plans are implemented
Maps of plantation establishment	Forest agencies, private sector	Plantation species will be established.
Species (or natural/plantation splits)	Remote sensing (either the same or other sensors as used for the time series)	Plantation species will be established. Natural species will have been cleared for other uses
Fire maps	Remote sensing Land management agencies	Change that occurs at the same time as fire is a fire
National parks and protected areas	Land management agencies	Changes are natural, unless otherwise noted
Climate or soils types	Resource agencies, meteorological agencies	Determine the types of crops and management that can occur in certain regions (e.g. no crops in a desert)

Stratification is important for several reasons. It can

‣ in the use of resources in preparing emissions and removals estimates

‣ assist in the management of uncertainties

‣ allow greater flexibility in reporting of monitored data (for example effectiveness of policies tailored to specific strata (forest types, risk types))

‣ enable tailoring of specific methods or data collection processes in different strata (for example it is much more difficult to measure deforestation using traditional optical methods in fragmented dryland forests than contiguous moist tropical forests).

Where relevant, stratification can be undertaken to distinguish between *managed* and *unmanaged* land in the various categories to meet the requirement of including only anthropogenic emissions and removals

using the managed land proxy[60]. While this approach to separating natural and anthropogenic emissions and removals is a proxy, it is the only generally practicable approach. Settlements and cropland are by definition managed, and it may be that all land in other categories can be considered as *managed*.

Stratification does not necessarily entail the use of maps, although usually[61] spatially explicit data (e.g. georeferenced NFI plots) are used. It may be on the basis of ground data or remotely-sensed data, or both in combination. Strata need to be sufficiently distinct to be identifiable and the boundaries of strata can change over time e.g. if the frontier of disturbance moves into areas of previously undisturbed forest. Information such as stocking densities (e.g. volume, biomass or carbon) and specialized map layers such as soils, site class, topography, aspect, dominant tree species or species clusters are commonly used for stratification. Examples of the stratification process can be found in McRoberts et al., 2002 and Olofsson et al., 2013.

Estimation of forest degradation, and the 'plus' activities of REDD+[62] may require finer resolution data (both spatially and temporally) than are being used currently by countries. Development of national capacity will help take advantage of technical developments as they become available[63]. For forest degradation auxiliary information on harvesting, whether legal or not, and other disturbances will help considerably.

Likelihood of human disturbance can also be the basis for stratification. Identification of areas at high risk of deforestation can assist in designing early warning and targeted monitoring processes. Data sources and tools are available to assist in this process (Chapter 4, Section 4.2.3). Box 20: Stratification and statistics and Chapter 5, Section 5.1 provide more information on stratification.

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[60] IPCC 2010 Technical Paper Revisiting the Use of Managed Land as a Proxy for Estimating National Anthropogenic Emissions and Removals. GPG2003 assumes all emissions and removals on managed land are anthropogenic

[61] Stratification is possible without spatially explicit data, e.g. based on frequencies of occurrences of various classes and guided by expert judgement and credible assumptions.

[62] Namely conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks.

[63] E.g. it is currently challenging to detect changes in canopy cover associated with degradation. In October 2013 GFOI and GOFC-GOLD held a workshop and published a report on technical developments in monitoring degradation.

> **Box 7: Plantation management in Kenya**
>
> In Kenya the standard plantation management practice following harvest is to put crops on the land for 1-2 years before replanting. In this case the remote sensing program will correctly see that the cover has changed from forest to crop. The attribution process notes that this is a human induced change in cover (due to the harvest). However, it is noted that the harvest occurred in a plantation (determined through knowledge of the species and stand maps from the Forest Information system). The policy and reporting rule set by the Government of Kenya is that the short crop cycle is part of plantation management. Consequently the land use does not change, (that is, it remains forestland) and all emissions associated with the harvest and removals from subsequent replanting reported under forestland. However, there is also the chance that the land will have been cleared and will not be returned to trees. If the land cover does not return for forest within a specified number of years, then a land use change is considered to have occurred at the time of harvest and the land areas are updated accordingly in the next report.

2.3.3 Forest reference emission levels and forest reference levels

An NFMS is likely to need to consider methodological issues associated with the construction of FREL and/or FRLs as benchmarks for assessing Parties' performances in implementing REDD+ activities. This implies consideration of the meaning of technical terms used in COP decisions, discussed in this section which is based on material previously published as GFOI MGD Module 3[64]. Other useful sources i) the GOFC-GOLD Sourcebook, ii) UN-REDD's Emerging approaches to Forest Reference Emission Levels and/or Forest Reference Levels for REDD+, also iii) the Technical considerations for FREL and/or FRL construction for REDD+ under the UNFCCC and the iv) World Bank Carbon Fund Methodological Framework. The World Bank Methodological Framework applies to pilot implementation under the Carbon Fund of the Bank's Forest Carbon Partnership Facility (FCPF), and has some requirements (e.g. concerning conservativeness, and to limit adjustments for national circumstances under the terms of decision 12/CP.17) which are more elaborated or restrictive than the COP decisions.

2.3.3.1 Consistency with the GHGI

Countries should ensure consistency between FRELs and/or FRLs, REDD+ emissions and removals estimates and GHGIs[65]. Consistency does not necessarily imply that the coverage of pools and gases is identical. This is because significant pools may mean different things in the REDD+ and the GHGI contexts, because the stepwise approach is not part of the GHGI, and because of the different objectives of both exercises – the GHGI is about estimating emissions and removals consistent with good practice whereas REDD+ is about effectively incentivizing actions to mitigate GHG emissions associated with REDD+ activities. If differences exist in the coverage of pools and gases between the FREL and/or

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[64] GFOI Module 3 provides advice on technical issues related to decisions 12/CP.17 and 13/CP.19. It can be downloaded from the GFOI website.

[65] Paragraph 8 of decision 12/CP.17 says that consistency between FRELs and FRLs and national GHGIs should be maintained. Paragraph 3 of the annex to decision 14/CP.19 requires estimating emissions and removals and changes of carbon stocks associated with REDD+ activities to be consistent with FRELs and FRLs.

FRL, REDD+ activity estimates and the GHGI, explanation of the reasons, rationale and impact of the differences should be provided to enhance transparency.

Generating estimates of emissions and removals associated with REDD+ activities using the GHGI methodologies in the GPG2003, including cross-references to the 2006GL, is described in Chapter 3, Section 3.1. Technical implementers may differ in the way they use IPCC Tiers and Approaches, and numerical data provided by IPCC or estimated nationally. Consistency can be enhanced if:

▸ the definition[66] of forest is the same for REDD+ GHG estimates, FREL and/or FRLs, and GHGI

▸ REDD+ activities are identifiable in the GHGI as IPCC categories, subcategories, or sums of categories or sub-categories. Table 7: Correspondence between REDD+ activities and IPCC categories and associated MGD advice shows the relationship between REDD+ activities, IPCC categories, and the sections of the MGD which provide advice on emissions and removals estimation. Stratification of land categories into subdivisions may help to increase transparency to assess consistency if REDD+ activities do not correspond to the whole categories within the inventory[67], e.g. because of a distinction between degradation and sustainable management, where sustainable management does not cover the entire managed forests, or because of interim use of subnational FREL and/or FRLs. If deforestation area does not take account of any regrowth or replanting after clear-cutting, it is sometimes called gross deforestation in the REDD+ context. This terminology is not consistent with the IPCC description of forest land (Table 3: IPCC top-level land categories for greenhouse gas (GHG) inventory reporting) which includes systems where there is the potential to regain forest thresholds. More generally, gross deforestation can also mean area deforested without taking account of increases in forest area from land converted to forest. Although in practice the differences may be small (because forest cover loss through clear cut is often linked to land use change in the REDD+ context), a clear description of what is included in the FREL and/or FRL is needed and there may be some need for reconciliation between categories used in the GHGI.

▸ activity data and emission/removal factors (or related quantities such as carbon densities) are the same for REDD+ and the GHGI. This may require sub-division if REDD+ categories do not correspond to whole categories within the inventory.

▸ REDD+ activities are part of the system of land representation described in Chapter 2 of the GPG2003 (or Chapter 3 of volume 4 of the 2006GL) with the sum of areas of land uses adding up to the national land area.

If estimates are made for subnational forest areas, emission calculation methods used should either be consistent with those used in national inventories, or Parties should consider whether there is a need to achieve consistency, perhaps by increasing stratification in the GHGI. This could be done at the iteration and cross-checking stage of the process. The decision tree in Figure 4: Institutional process for ensuring consistency between REDD+ estimates and GHGI shows how institutions can interact to achieve consistency.

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[66] Including also on how managed forests are defined.

[67] In the case of deforestation, to summation over inventory categories – namely conversion of forest to other land uses

Table 7: Correspondence between REDD+ activities and IPCC categories and associated MGD advice

REDD+	IPCC Land Use Change Descriptions	MGD Advice
Reducing emissions from deforestation[a,b]	Forest land converted to other land uses	Chapter 3, Section 3.1.1
Reducing emissions from forest degradation	Forest land remaining forest land	Chapter 3, Section 3.1.2
Sustainable management of forests	Forest land remaining forest land	Chapter 3, Section 3.1.3
Conservation of forest carbon stocks	Forest land remaining forest land	Chapter 3, Section 3.1.3
Enhancement of forest carbon stocks (within an existing forest)	Forest land remaining forest land	Chapter 3, Section 3.1.3
Enhancement of forest carbon stocks (afforestation of land not previously forest, reforestation of land previously converted from another land use)	Other land uses converted to forest land	Chapter 3, Section 3.1.4

Notes: a) Emissions from "gross deforestation" may be greater than those from deforestation considered in the IPCC inventory methodology because gross deforestation does not take account of forest regrowth or replanting after the clear-cutting. b) If gross deforestation is used then it will also affect the area and emissions estimates in forest remaining forest. Harvests seen as deforestation need to be separated from those that are not. This separation will also influence emissions attributed to degradation.

Figure 4: Institutional process for ensuring consistency between REDD+ estimates and GHGI

Note: a. Consistency will be considered as part of the technical analysis process summarized in 6.3.
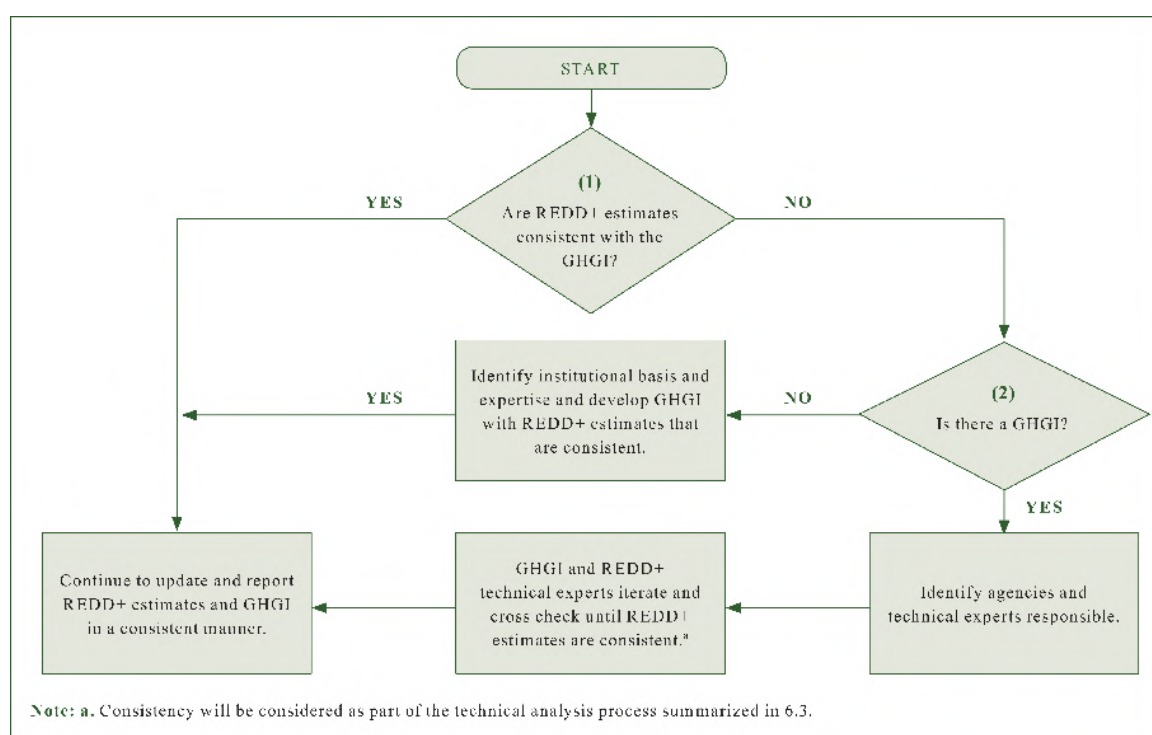
Considerations at the decision points in the tree are as follows:

Decision Point 1: Are REDD+ estimates consistent with the GHGI?

> As GHGI and REDD+ estimates have different purposes differences may exist in how estimates are generated. This may be related to opting to report REDD+ at a sub-national level as an interim approach, or the availability (or lack) of national data for specific REDD+ activities. If differences do exist in, for example, the coverage of pools and gases or the geographical scope, an explanation of the reasons, rationale and impact of the differences should be provided to enhance transparency.

Decision Point 2: Is there a GHGI?

> Developing countries are required to submit a national inventory of anthropogenic emissions by sources, and removals by sinks, of all greenhouse gases (GHGs) as part of their national communications and biennial updates.

2.3.3.2 Use of historical data

GHGIs may not be produced every year, but once consistency with the GHGI is established, the historical data used to estimate FREL and/or FRLs need not be restricted to years for which GHGIs are available, provided the relevant time series are internally consistent. The great majority of countries that have submitted a FREL/FRL to date have proposed averaging historical time series to establish representative historical levels of emissions and removals. Consideration of variation within the historical period can assist with analysis of drivers or effectiveness of policy interventions. Although the UNFCCC does not specify a period, ten to fifteen years could be considered a feasible and useful period for time series because it allows sufficient time for the average to be representative of current conditions and yet provides an opportunity for variation between years to be studied for possible relationship with drivers.

The Landsat archive provides data from which time series for GHG emissions and removals associated with REDD+ activities can be estimated, especially for deforestation[68], using the methods set out in Chapter 3, Section 3.1. Historical Landsat data are freely available as a core data set (Chapter 4, Section 4.1.2) and can be accessed via the United States Geological Survey (USGS) Data Centre[69]. Use of global data sets may help make progress before national mapping capacity is fully established. The trade-offs between national mapping and the use of global datasets is set out in a Chapter 4, Section 4.1.7.

Once established, time series can be extended and/or revised as new data become available and the information incorporated into updated FRELs and/or FRLs. Table 8: Different types of reference levels describes some different types of reference level consistent with COP decisions and Figure 5: Use of historical data for developing FREL/FRLs suggests a decision tree for choosing between them. The most appropriate FREL and/or FRL construction approach may change over time; for example as understanding of drivers improves a Party could alter the historical period or construction approach to reflect better expected emissions/removals in absence of REDD+ implementation. Also the most appropriate form of reference level may be different for different REDD+ activities, depending on the type of historical data available for quantifying the activity.

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[68] Higher resolution data may be needed for degradation and other activities.

[69] The continuing work of the GFOI to ensure the long term availability of space data is detailed on the GFOI webpage.

Figure 5: Use of historical data for developing FREL/FRLs

Note: a. Detailed advice on how to generate estimates of REDD+ emissions and removals consistent with IPCC guidance for GHGI is presented in 3.
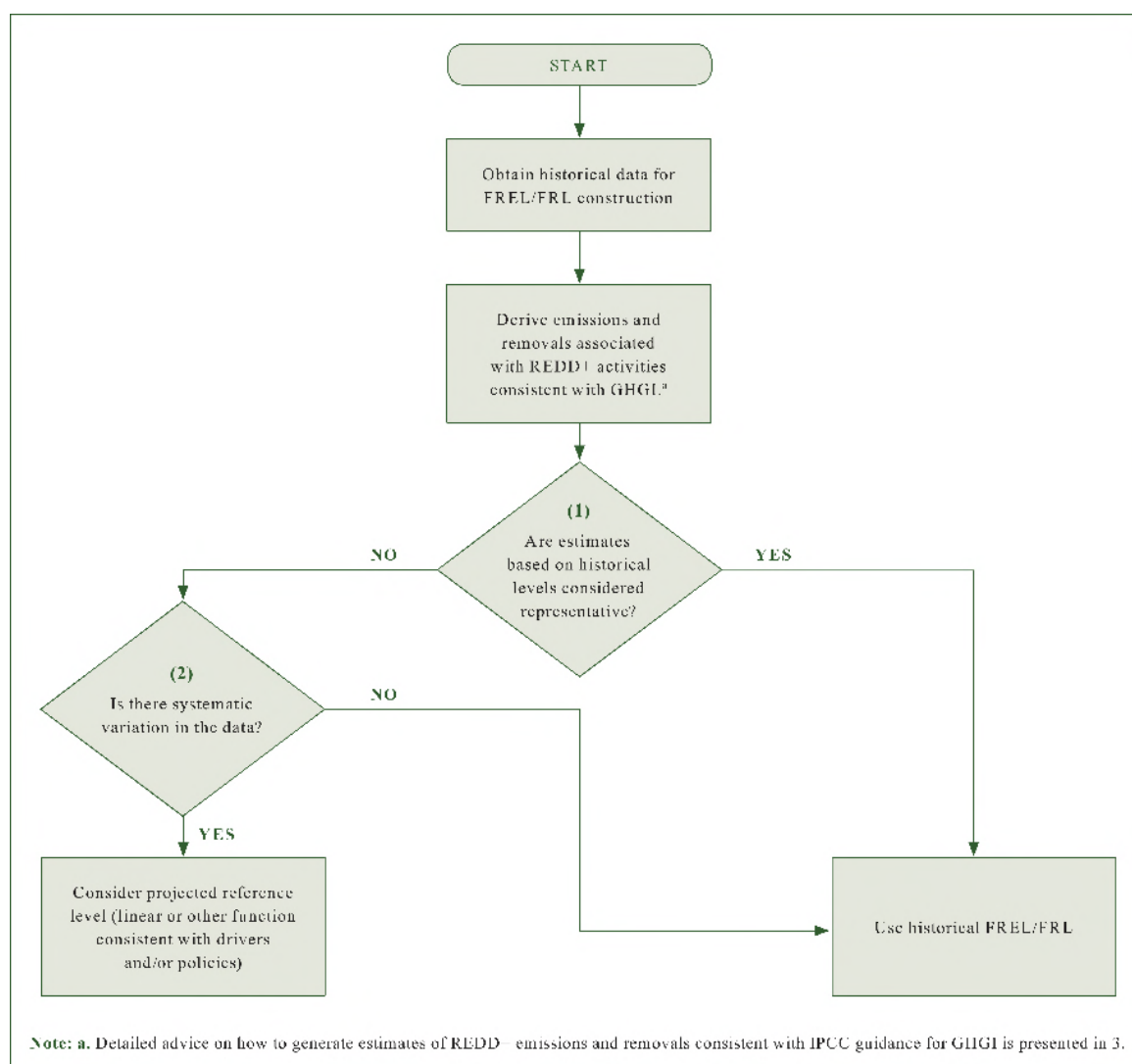
Considerations at the decision points in the tree are as follows:

Decision Point 1: Are estimates based on historical levels representative?

> This can be the case if the historical data show only statistical scatter about the mean, or else a trend variation that can be captured by one of the historical methods 1) to 3) in Table 8.

Decision Point 2: Is there a systematic variation in the data?

> This is likely to require annual data points to determine and users should consider whether one of the historical methods would in fact be sufficient. Variation could show generally increases or decreases over time in the REDD+ activity of interest. The trend fitted could be linear or some other function (e.g. logarithmic) if this gave better representation, or a projection based on model simulation. The methods are 4) and 5) in Table 8.

Table 8: Different types of reference levels

Type of reference level	Description	Notes	Possible reasons for choice
1.Historical average	Average emissions or removals, generally over a defined period (10-15 years could be considered useful to average out inter-temporal variability)	Assesses achievement of REDD+ actions relative to a fixed historical period.	This is the simplest option and could be the easiest choice initially. The fixed historical period becomes less relevant the further one goes into the future, but could be updated periodically, which yields Type 2.
2.Rolling average	As for the historical average but updated, probably every 5 years with the averaging period kept at the same duration but shifted accordingly	The historical period lags the period used for assessment by 10 years or so.	Gives closer tracking between REDD+ activities and the FREL and/or FRL than Type 1. Could adopt Type 1 initially then move to Type 2.
3.Cumulative average[70]	As (1) but newly available historical data extends the averaging period	Approaches the current value more slowly than (2). Re-calibration every 15 years or so could be useful, consistent with the range considered for simple historical averages.	To give greater emphasis to historical conditions than is achieved by Type 2
4.Trend extrapolation	Extrapolation of trend fitted to historical data	Needs good confidence that the past trend is likely to be representative of the future. Otherwise needs frequent updating. The trend fitted could be linear or some other function (e.g. logarithmic) if this gave better representation.	If there is a clear trend in historical data.

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[70] Cumulative average has also been called dynamic mean (see Technical report on the technical analysis of the technical annex to the first biennial update report of Brazil submitted in accordance with decision 14/ CP.19, paragraph 7, on 31 December 2014)

Type of reference level	Description	Notes	Possible reasons for choice
5.Other projection	Projection based on model simulation	Needs good understanding of the effect of drivers (based on historical data) and policies, and solid basis and documentation of the assumptions made. For credibility, models used for the projection should be transparent and able to replicate past levels and trends[71], possibly including expectations underlying the forest transition curve.	If there is a clear trend in historical data with understanding of the causes

2.3.3.3 Adjustments

Under some conditions, historical data could be unrepresentative of what would happen in the absence of REDD+ implementation, and therefore less useful as a benchmark for assessing performance in implementing REDD+ activities. For example, this could be the case in a Party with high forest area and low deforestation rate facing new pressures (e.g. to develop agriculture so as to create socio-economic benefits for rural people) to deforest or to degrade forest ecosystems. If the effect can be quantified, the FREL and/or FRL may be adjusted. The decision tree Figure 6: Considerations for making FREL/FRL adjustments suggests a framework for assessing when this could be the case.

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[71] Transparency in models is discussed in the report of the IPCC Expert Meeting on Use of Models and Measurements in GHG Inventories (Sydney 2010).

Figure 6: Considerations for making FREL/FRL adjustments

Note: a. It may be useful to compare the adjusted FREL and/or FRL with other countries in the region and (in the case of adjusted deforestation rates at least) with regional or global rates since these represent the range of pressures to which forests are exposed, and adjustments in excess of these rates may seem inconsistent with the purpose of REDD+.
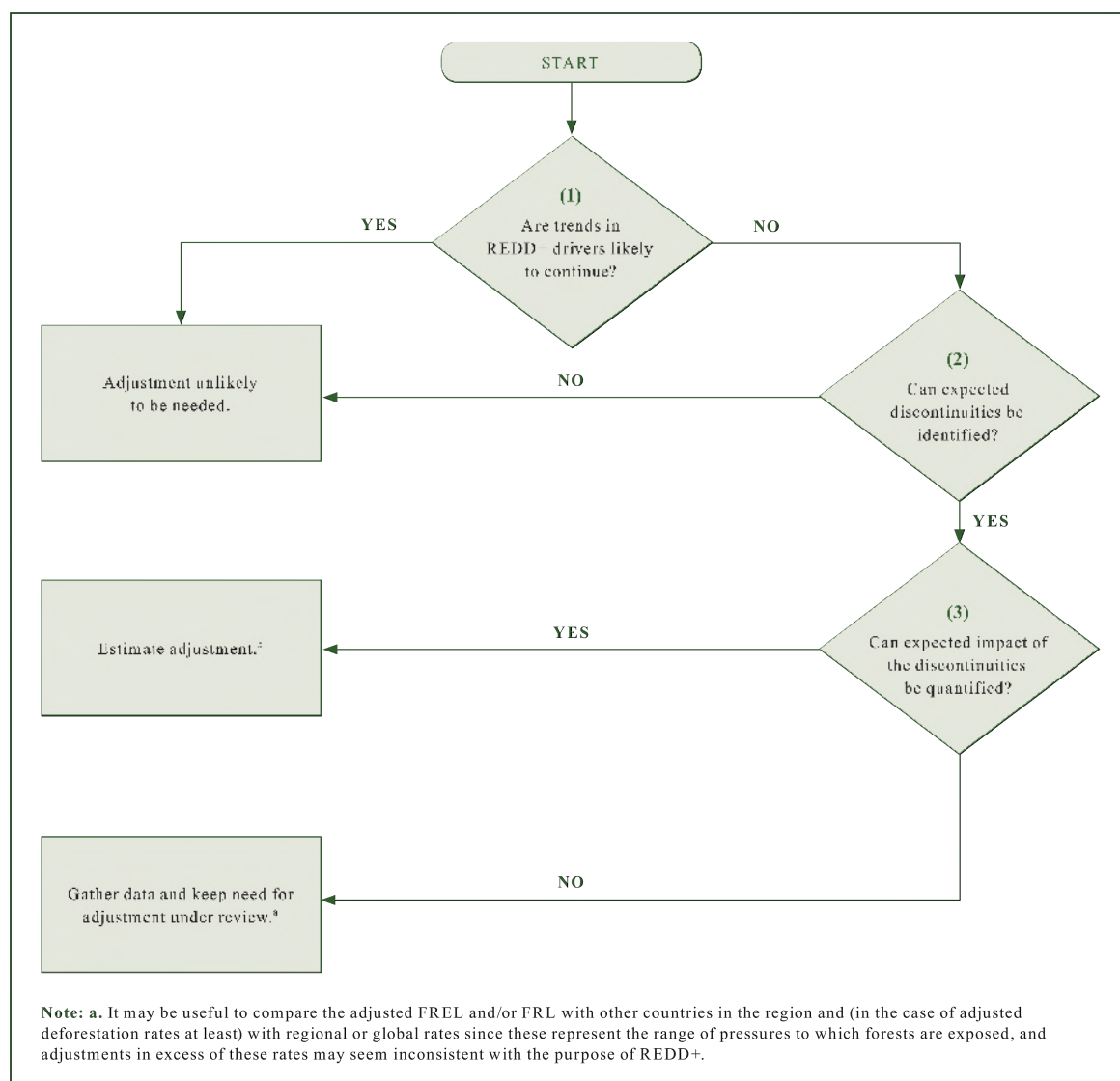
Considerations at the decision points in the tree are as follows:

Decision Point 1: Are trends in REDD+ drivers likely to continue?

Continuation of existing trends in drivers (which includes drivers remaining approximately unchanged) is unlikely to give rise to the need for an adjustment because these trends are what has driven past emissions and removals from REDD+ activities and unless there is a discontinuity of some sort this will probably continue. Of course the relationship between drivers may evolve over time, but this can be captured in the updating of the FREL and/or FRL, or by a projected FREL and/or FRL level (see Table 8: Different types of reference levels) without requiring an adjustment.

Decision Point 2: Can expected discontinuities be identified?

If discontinuities from past trends can be identified, an adjustment may be justified - for example there may be known step changes in land use change plans due to large infrastructure projects or agricultural expansion in forest areas which are likely to affect human impacts on forests. Identifying discontinuities relies on auxiliary data such as knowledge of driver motivations and

opportunities and/or an understanding of the countries state of economic and social stability and population growth.

Decision Point 3: Can expected impact of the discontinuities be quantified?

Quantification of the expected impact of the discontinuities could be done by direct estimation of the effect of the discontinuity (new infrastructure development etc. beyond past trends) or by more sophisticated modelling, though as noted in the context of FREL and/or FRL based on model simulation projections (Table 8: Different types of reference levels; type 5) the uncertainties in model estimates of this kind are likely to be large, and models that are calibrated to past conditions may not perform well if discontinuous changes are expected due to variables or factors not included in the model. It may be useful to compare the adjusted FREL and/or FRL with other countries in the region and (in the case of adjusted deforestation rates at least) with regional or global rates since these represent the range of pressures to which forests are exposed, and adjustments in excess of these rates may seem inconsistent with the purpose of REDD+.

2.3.3.4 Uncertainties

The COP decisions that make up the Warsaw Framework on REDD+ refer to the Copenhagen REDD+ decision 4/CP.15 which requires Parties to establish NFMS that *provide estimates that are transparent, consistent, as far as possible accurate, and that reduce uncertainties, taking into account national capabilities and capacities*. Use of IPCC guidance to quantify emissions and removals requires quantification of uncertainties consistent with the good practice principle of neither over- nor under-estimates so far as can be judged, and uncertainties reduced as far as practicable (IPCC, 2003; preface).

Uncertainties in annual emissions or removals associated with REDD+ activities can be estimated using the methods outlined in the MGD (Chapter 5, Section 5.3), consistent with IPCC Guidance [72]. In assessing performance in implementing REDD+ activities (e.g. deforestation) emissions and removals estimates in the assessment period are compared against the FREL/FRL to estimate REDD+ results. To the extent that each estimate is independent, one can assume that the uncertainties associated with successive estimates of areas deforested are uncorrelated. On the other hand for emission/removal factors (carbon densities) to estimate emissions, the errors may be correlated if the same set of plots is used to establish the carbon densities used in successive calculations. As a consequence, to estimate the overall uncertainty in emissions reduction requires combining the uncertainty in the activity data (uncorrelated) with the uncertainty in the emission factor (which may be correlated). The calculation of uncertainties associated with activity data are described in Chapter 5, Section 5.1.5, and the calculations for uncertainties in emission/removal factors, including both the correlated and uncorrelated cases, are described in Chapter 5, Section 5.2.6, which contains a Box 27: Calculation of the uncertainty of emissions/removals factors under sampling with replacement showing how this approach may be applied to comparing emissions and removals estimates during the assessment period against the FREL/FRL, in the context of deforestation.

Estimates of uncertainty can be used to guide future developments and continuous improvement of the system and its estimates. Used in combination with key category analysis, it can help to identify categories that have the greatest contribution to overall inventory uncertainty in order to make the most efficient use of available resources. By identifying these categories (Section 2.2.3) efforts and improve overall estimates can be prioritised.

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[72] GPG2003 section 5.1 and 5.2 or 2006GL, volume 1, section 3.2.3.1.

2.3.3.5   Stepwise approach and updating

Under a stepwise approach[73] FREL and/or FRLs may be improved by better data or methodologies, and additional pools and gases can be added over time. If the provision for inclusion of better data is interpreted as allowing for this, Parties using a stepwise approach could start with the activity considered to be the most significant, and include all significant pools associated with it, as indicated by criteria A to C in Section 2.2.3 above. This should ensure prioritization of the most relevant sources. Subsequent steps would add other significant activities – e.g. forest degradation, which is likely to become easier to monitor in the foreseeable future through increased availability of high resolution data and other types of remote sensing (Chapter 4, Section 4.1). Future improvements in data could also involve establishment of national forest inventories and intensive monitoring sites, for improved forest policies and resource management, and improved reporting capabilities, including for REDD+.

A stepwise approach as a way to incorporate better data or methodologies is related to the more general requirement for Parties to update FREL and/or FRLs periodically as appropriate, taking into account new knowledge, new trends and any modification of scope and methodologies[74]. When updating, Parties should maintain methodological consistency between the REDD+ GHG estimates and the FREL and/or FRLs. This may entail improvements to the GHGI as well as to the FREL and/or FRL estimates; the point is that they should be mutually consistent. Paragraph 15 of decision 12/CP.17 establishes a process for the technical assessment of updated, as well as newly submitted, reference levels.

2.3.3.6   Number of reference levels per Party

Annexes to decisions 12/CP.17 and 13/CP.19[75] refer to '…[a Party's]… forest reference emission level and/or forest reference level'. The idea of FRELs corresponds to the emissive activities (deforestation and forest degradation) which can be summed together as one FREL. FRLs allow for inclusion of the activities that can remove CO_2 from the atmosphere – namely conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks[76]. FRLs also allow for the summation of the activities that can result in removals – together, and with the emissive activities. Summation should avoid double counting between FRELs and FRLs.

In the case of national FREL and/or FRLs, the simplest approach could be that each Party decide to have at most one FREL and/or one FRL which would be summed over all REDD+ activities included by the Party. Having one FREL and/or FRL could help increase methodological consistency, reduce monitoring costs and uncertainties, and reduce the risk of displacement.

Changes in activity coverage of FRELs and/or FRLs will be accompanied by technical reassessment.

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[73] See paragraph 10 of decision 12/CP.17

[74] See paragraph 12 of decision 12/CP.17

[75] Decisions 12/CP.17 and 13/CP.19 are respectively the decisions on reference level submission and its technical assessment from the Durban and Warsaw COPs

[76] Short-term emissions (e.g. due to harvest prior to replanting) may occur in these other activities. Also when other forest values are taken into account, long term reduction in carbon stocks could be associated with sustainable forest management which could then be treated as part of a FREL.

2.3.3.7 Subnational activities

Subnational FREL and/or FRLs may be developed as an interim step on the way to development of national FREL and/or FRLs[77]. In this case development of NFMS should …*include monitoring and reporting of emissions displacement at the national level, if appropriate, and reporting on how displacement of emissions is being addressed, and on the means to integrate subnational monitoring systems into a national monitoring system*[78].

Integration into national monitoring systems will be easier if the boundaries of subnational activities and hence their associated FRELs and FRLs correspond to boundaries in the stratification process of the national GHG inventory since this will help deliver consistency with the GHGI.

If the national FREL and/or FRL already exist as a sum of subnational FREL and/or FRLs[79] then estimates of displaced emissions will be unnecessary for international reporting. Otherwise evidence, to establish whether there is a zone of influence outside the boundary of the subnational FREL and/or FRL and support estimates of displaced emissions, could be gathered by remote sensing to detect signs of disturbance, or by ground sampling. Stratification of activities at the national or subnational scale may also be useful to identify areas associated with drivers and to demonstrate the effect of actions taken.

2.3.4 Quality assurance and quality control

Though not specifically required by REDD+ decisions, it is useful to implement QA/QC including internal review procedures in the development of estimates. A QA/QC system contributes to the objectives of good practice in inventory development[80], namely to improve transparency, consistency, comparability, completeness, and accuracy of national greenhouse gas inventories. The outcomes of QA/QC processes may result in a reassessment of inventory or category estimates or uncertainties, and to subsequent improvements in the estimates of emissions or removals. For example, the results of the QA/QC process may point to particular variables within the estimation methodology for a certain category that should be the focus of improvement efforts.

QA and QC are defined by IPCC as follows:

▸ **Quality assurance (QA)** – a planned system of review procedures conducted by personnel not involved in the inventory development process.

▸ **Quality control (QC)** – a system of routine technical activities implemented by the inventory development team to measure and control the quality of the inventory as it is prepared.

Section 5.5.2 of the GPG2003 introduces the idea of a QA/QC plan, which is described in more detail in volume 1, section 6.5 of the 2006GL. A written QA/QC plan is fundamental to a QA/QC system. This plan outlines QA/QC activities performed, the personnel responsible for these activities, and the schedule for completing these activities.

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[77] See paragraph 11, decision 12/CP.17

[78] See paragraph 71(c), footnote 7 of decision 1/CP.16

[79] This possibility is recognised in paragraph 71(b), footnote 6 of decision 1/CP.16

[80] Section 5.5 of GPG2003 discusses QA/QC or volume 1, chapter 6 of 2006GL (which discusses QA/QC in general, and volume 4, chapter 4 of 2006GL which provides additional material on QA/QC issues relating to forests).

An effective QA/QC plan contains the following four core elements:

1. Coordination

A QA/QC coordinator is responsible for implementing the QA/QC plan. In this role, the QA/QC coordinator:

▸ Clarifies and communicates QA/QC responsibilities

▸ Develops and maintains QA/QC checklists appropriate to various roles

▸ Ensures the timely and accurate completion of QA/QC checklists and related activities

▸ Develops an overall QA/QC timeline and when external reviews will occur

▸ Manages and delivers documentation of QA/QC activities for documentation and archiving

▸ Coordinates external reviews of estimates and reports and ensures that comments are incorporated.

2. Review procedures

Although general QC procedures are designed to be implemented for all categories and on a routine basis[81], it may not be necessary or possible to check all aspects of input data, parameters and calculations every year. A representative sample of data and calculations from every category may be subjected to general QC procedures each year. In establishing criteria and processes for selecting sample data sets and processes, it is good practice to undertake QC checks on all parts of the system over an appropriate period of time as determined in the QA/QC plan.

When undertaking an internal review of MRV procedures, methodologies, and outputs it is recommended to ensure that[82]:

▸ Sufficient independent expertise is available to conduct the internal review;

▸ Applied review methods are transparent, rigorous and scientifically sound;

▸ Review results are reasonable and well- explained;

▸ Review approach and findings are documented and considered in continuous improvement processes.

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[81] GPG2003 section 5.5 or 2006GL, volume 1, section 6.

[82] Adapted from GPG2003 section 5.7.3.

Box 8: Suggested internal review checklist for REDD+ suggests a checklist for internal verification purposes. When an internal review has been undertaken, it would be useful to report and document the following items:

- information that has been verified internally

- criteria that were used for the selection of verification priorities

- verification approaches, along with relevant data that were collected

- any limitations in the approaches that have been identified

- comparisons that have been performed with independent inventories, datasets, scientific literature, or other studies

- feedback received from external reviewers, with a summary of key comments, and reference to actions taken to address such comments have been addressed

- main conclusions of the verification

- actions taken as a result of the verification process

- any recommendations for inventory improvements or research at national/international level arising from the findings with their prioritization; together with identification of capacity building needs where relevant.

3. Documentation and archiving procedures

A documentation and archiving system is needed for any monitoring system. Documentation and archiving allow estimates to be reproduced, safeguards against data and information loss, and supports internal and external verification processes.

An effective documentation and archiving system serves as institutional memory and should store information with enough detail to support new teams or team members in their roles. This will reduce duplication of work and make efficient use of resources. Archiving of material should enable easy access to the documentation and references. Where possible all information should be stored in a central location. Depending on the institutional arrangements established for REDD+ reporting (Chapter 1) the documentation and archiving system may be the same for national GHGI development and REDD+ reporting.

As a guide, the following information should be documented and archived related to REDD+ estimates:

- final reports (i.e. FREL/FRLs, REDD+ technical annexes to the BUR, other material submitted to the UNFCCC)

- activity data, also sources for information, contact persons, other contact information

- emission and removal factors and the reasoning for their choice

- methods used, including spreadsheets, models, instructions how to do the calculations, how to apply the models, reasoning for choices made

- archive by submission or inventory year

- references

- expert judgment (documentation, contact information)

- changes made and recalculations

- results of key category analysis

- uncertainty analysis

- results of QA/QC measures

- improvement plan

- archiving plan

- review findings and responses.

A responsible person (an archive manager or archive coordinator) should be nominated to maintain the documentation and archiving system, and a plan made for updating the documentation and the archive. This plan could include operational elements such as what can be changed or updated, and by whom; when and how updates or changes are made, and who has access to change documentation within the archive, noting any special procedures for archiving of confidential data.

The system need not be expensive or complicated and may be electronic and/or hard copy, and should be located in a specified location, central to the NFMS. There are a number of sources available to assist in developing documentation and archiving systems. The ISO quality management and environmental management standard outlines a useful framework which can be built upon over time.

4. Effective use of resources in delivering MRV requirements

Establishing and maintaining an NFMS required significant upfront and ongoing commitment and resources. When well designed, an NFMS can support a number of national and international reporting opportunities. In the context of REDD+, countries and international agencies should consider the most

effective use of human and financial resources to deliver associated MRV requirements. This entails considerations such as:

▸ which pools and activities are likely to be significant in determining the level and trend in emissions and removals

▸ availability and cost of remote sensing data

▸ need for pre-processing and associated costs

▸ assessment of existing data sources and the costs associated with acquiring and processing new sources of data

▸ existence of ground-based data sets and need for new or supplementary surveys

▸ availability and suitability of existing tools for integration data and producing required reports

▸ national support resources, both human capacity and financial to implement, improve and operate the system in the long term.

▸ level of support and incentive payments and long-term costs

▸ co-benefits of taking action and opportunity cost of activities foregone

▸ opportunities for integration with broader land use monitoring systems for GHG inventory purposes, other reporting processes (such as FRA) or improving management of resources that will facilitate the flow of information, the co-ordination of different institutions and the consistency across reporting activities.

Effectiveness of finance requires consideration of long term monitoring costs. The design of a REDD+ policy framework can have a significant impact on the long term operational and improvement costs. REDD+ policies and MRV monitoring functions will co-evolve and therefore MRV processes need to be designed to serve known current and future policy requirements as well as being conditional on technical capabilities, initial development, and operational costs (Böttcher et al., 2009).

Long term improvement and operational costs, as well as short term implementation costs should be considered. Linkages to other permanent national monitoring activities, such as NFIs, for example should be prioritised. There should also be consideration of how to leverage existing data collection platforms and to establish systems to support other national and international reporting opportunities

and requirements. The following considerations should therefore be part of the design process and will assist in reducing the risk of a financially unsustainable MRV program, based on sound science:

▸ MRV functions should be considered as a program, not a project, and will need to continue indefinitely.

▸ MRV design should be based on policy and reporting needs, country specific circumstances and definitions, financing mechanism, available technology and prospects for results-based payments. This will require close collaboration between policy makers and technical officers.

▸ evolution of annual budgets through all phases of the programme should be considered from the outset as part of the design and implementation stage to help ensure the program can be adequately funded.

▸ sources of funding is also a consideration as donors may be more likely to provide funds for design and to support implementation phases, but program funds for improvement will likely fall to countries in the longer term.

▸ the challenge of securing long term funding for the operational phase of the MRV program should not be underestimated given increasing pressure to show cost-effectiveness.

▸ integration of data in multipurpose data platforms (one data platform policy) should be considered as a way to seek for cost efficiency and long term sustainability.

The cost effectiveness of an MRV program design will depend on the balance between MRV and other REDD+ costs and the benefits of participating in REDD+ activities as well as the possibilities for using REDD+ as part of a broader land use monitoring platform. The outcome of these considerations will differ significantly from country to country. Cost effectiveness entails saving resources relative to alternative approaches, and not entailing disproportionate additional expenditure given the benefit anticipated.

If MRV monitoring costs are shared between sectors, an integrated monitoring system could have multiple benefits for non-REDD+ land use management (Böttcher et al., 2009). If the monitoring costs associated with co-benefits in other sectors such as optimized land management, improved fire management, agricultural monitoring, and monitoring other environmental values such as biodiversity are included, overall monitoring costs are likely to be lower than separate monitoring for each.

Appendix A gives information on establishment and operational costs based on FCPF budgets.

GFOI has improved international cooperation in the collection, interpretation, and sharing of earth observation information and sees this as an important way to increase cost-effectiveness to assist decision makers as they design their MRV programs.

Box 8: Suggested internal review checklist for REDD+

Checks

  ▸ Are all data and assumptions used for estimating emissions and removals transparently documented for all selected/important activities, carbon pools and gases?

  ▸ Are the methods applied consistent with methods used to calculate emissions and removals from the LULUCF sector reported in GHGIs to the UNFCCC?

  ▸ If some REDD+ activities or carbon pools have been omitted, does the report explain why?

  ▸ Are all gases required by the IPCC guidance and guidelines included? If not are explanations for the omission provided?

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

Comparisons (one or more comparisons should be made)

  ▸ Compare REDD+ estimates with independently prepared estimates for the same areas/ activities or compare regional sub- sets of national REDD+ estimates with independently prepared estimates for those regions.

  ▸ Compare activity data and/or emission estimates used in developing the REDD+ estimates with independent international databases and/or other countries.

  ▸ Compare REDD+ estimates with results calculated using another tier methodology, including IPCC tier 1.

  ▸ Compare REDD+ estimates with available high- intensity studies and experiments.

  ▸ Compare land areas and biomass stocks, and any other stock for which data are available, used in REDD+ global data sets.

Comparisons of uncertainties (one or more comparisons should be made)

  ▸ Compare uncertainty estimates with uncertainty reported in the literature.

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

Direct measurements

  ▸ Cross check with available independent direct measurements (which may be available from local forest inventories (if not already used in the estimates), detailed growth measurements and/or measurements made on particular ecosystems for research purposes).

Many data checks can be automated both to allow more time for QC that needs to be done manually. Automated checks include checking ranges on input and output data against previous estimates, and checks against known points of truth. Automated checks often generate a list of suspicious data rather than producing a full pass/fail. This allows manual intervention to check the potential errors. Even with automated systems there should be a degree of random checks to provide confidence that the automated systems are not missing issues, and to improve them if they are.

Source: Adapted from GPG2003, Box 5.7.3.

2.4   Guiding principles – Requirements and design decisions

▸ Well defined requirements and associated design decisions underpin the creation of a national forest monitoring and reporting system and should:

> ❯ reflect decisions of the UNFCCC COP in setting the scope of REDD+ activities and the overall policy framework;

> ❯ be consistent with methodological guidance developed by IPCC for greenhouse gas inventories for estimating greenhouse gas emissions and removals; and reflect efficient use of existing institutions and frameworks to minimize establishment and operational costs.

▸ National Forest Monitoring Systems (NFMS) should build on existing systems to make effective use of resources and provide data that are transparent and consistent over time and suitable for Measurement Reporting and Verification including some or all of the following design decisions:

> ❯ data collection, analysis, QA/QC and archiving processes

> ❯ forest definition and stratification descriptions to enable land use/land cover reporting

> ❯ consistency between reference levels, REDD+ reporting and GHGI reporting

Chapter 3   Methods and approaches

This chapter systematically describes estimation methods for the five REDD+ activities in manner consistent with the IPCC guidance and presents integration frameworks that facilitate the estimation of emissions and removals. Guidance is provided throughout this chapter to assist in the selection of appropriate estimation methods and integration frameworks.

3.1   Estimation methods for REDD+ activities

Since IPCC guidance does not refer to REDD+ activities specifically, MGD advice makes the necessary links between IPCC guidance and REDD+ activities. The MGD does not reproduce IPCC guidance, but cross-references it where necessary. The GPG2003 provides guidance on data sources which need to be used in conjunction with the remote sensing and ground-based data, e.g. on carbon densities for non-forest land uses or emissions and removals factors associated with non-CO_2 greenhouse gases.

The MGD assumes that there should be methodological consistency between the estimates, and that double-counting of emissions and removals is to be avoided. The advice provided below achieves consistency by suggesting the same forest stratification and estimation methods across the range of REDD+ activities. Potential double counting is avoided by providing advice on the circumstances under which forest degradation and the other REDD+ activities should be estimated together. Remote sensing methods can also have rules to ensure that any pixel or mapping unit is not double counted between REDD+ activities.

The method for combining changes in area and carbon density changes will depend on the sampling or modelling approach adopted by the NFMS. In the gain-loss methods described below, the area of land affected by REDD+ activities is multiplied by the change in carbon per unit area (the carbon density change) in the various pools to estimate the total net carbon emissions or removals. The methods described in this chapter are to be used with Chapter 4 and Chapter 5, which describe the acquisition of area and carbon density data, and associated uncertainties, and includes correction of area data for bias. The methods assume that annual estimates will be made, including the correction for estimated bias, although in principle other periodicities could be used.

Where NFIs or other design-based sampling approaches (including model-assisted inference) are used, the mean carbon densities can be estimated from the sample, which may be stratified by forest type or disturbance regime to increase sampling efficiency. Where model-based inferential approaches are used, carbon densities for the areas in question are inferred from the model being used. and change in carbon density is modelled for each type of forest to non-forest conversion. The method assumes that NFIs, where they exist, will be used as a source of plot data rather than extended to estimate REDD+ activities directly. Appendix B contains a discussion on sampling.

It is most likely that countries will use medium resolution optical data to implement MGD advice. Other types of data, including high resolution optical data and radar are likely to be used increasingly as availability improves and processing techniques are further developed[83]. Advice on methods based on

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[83] There is no generally agreed definition of the terms coarse, medium and high (also called fine) resolution, and therefore for complete clarity it is better to specify resolution numerically. Where these terms are used in the MGD, coarse refers to spatial resolutions above 250 meters, medium to 10 to 80 metres and high to better than 10 metres. These ranges are determined by the methodologies described in the MGD, and the remote

transitions and trends between strata and within strata is included in Section 3.1; Section 3.2 includes advice on methods that can track individual changes in pixels or mapping units over time.

3.1.1   Estimation of emissions from deforestation

Deforestation is the conversion of Forest Land to another land category. In IPCC terms the possibilities are Cropland, Grassland, Wetlands, Settlements or Other Land. The total emissions from deforestation will depend on how much carbon was in the forest at the time of clearing, how the land was cleared and the subsequent land use. For example loss of soil carbon is likely to be greater under cropping than under permanent pasture, and will continue for some time as the disturbed pools come to new dynamic equilibrium. If deforestation is accompanied by drainage of organic soils, emissions will persist as long as the soil remains drained or organic matter remains[84].

Chapter 3 of the GPG2003 includes guidance for estimating emissions and removals associated with conversion from one land category to another covering all pools and gases with some simplifications at Tier 1. It does not include deforestation as a single conversion category because the guidance is organised around making estimates of the effect of conversion *to* the new category, rather than *away* from the previous one. This means that Chapter 3 of the GPG2003 has no specific methodological guidance for deforestation labelled as such. Since deforestation is an activity recognised under the KP, Chapter 4 of GPG2003, which contains supplementary guidance for estimating and reporting on KP activities, does cover deforestation in the KP context, as does section 2.6 of the IPCC 2013 KP Supplement.

The MGD advice is to estimate deforestation as the sum of conversions from Forest Land to other land uses (usually Cropland, Grassland, or Settlements). Section 4.2.6 in Chapter 4 of GPG2003 cross references the sections in Chapter 3 of GPG2003 needed to do this. The relevant sections are shown in Table 9: Potential conversions contributing to deforestation and corresponding IPCC Guidance on emissions estimation below and can be used in conjunction with the advice below to estimate emissions from deforestation. The steps are:

▸ consider successively the five potential forest conversions identified by the index i

▸ if the conversion corresponding to the current value of i does not occur then its additional contribution to deforestation emissions for the year in question is zero

▸ if the conversion does occur then emissions from the newly converted area should be estimated using the methodology provided in the corresponding section of GPG2003 or where applicable the 2006GL

Even if the ith conversion did not occur in the current year, there may be emissions arising from the delayed effects, e.g. in the soil carbon pool[85] of conversions of this type that occurred in previous years. In these cases it is necessary to use historical data in estimating deforestation emissions and an assessment made of the eventual land use following deforestation. IPCC Tier 1 methods generally assume that the changes occur over 20 years and that land ceases to be in a conversion category 20

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sensing data available via the SDCG core data streams. Intermediate resolutions between 80 and 250 would by default be categorised as coarse.

[84] See section 2.2.1, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands

[85] Lagged effects are considered in the soil carbon pool at Tier 1. Higher Tiers may consider the dynamics of other pools explicitly.

years after the conversion occurred. Therefore it would be reasonable to base deforestation emissions on conversion data covering the past 20 years unless (as discussed in Box 5: Land use and REDD+ activities above) a country does not yet have the tracking capacity required, or wishes to use a longer period, e.g. to capture on-going emissions from drained organic soils, or wishes to reassign land to various REDD+ activities, probably of methodological or policy rationalization. In all cases countries should ensure that the REDD+ emission and removals estimates and the estimation of the FREL and/ or FRL are on a consistent basis

If data are not available for such a period then deforestation emissions can still be estimated, but they will show a transient effect as the estimated lagged emissions accumulate. In all cases it is important that the actual emissions estimates and the FREL or FRL are estimated on a consistent basis. Not accounting for these lagged emissions can lead to bias in the FREL/RL and emissions reporting. Where the forests are stratified, for example according to the Forest Resources Assessment (FAO & JRC, 2012) into *primary forest*[86], *modified natural forest*[87] and *planted forest*[88] (which may also have various sub-strata such as wet, moist, montane etc.) the guiding steps above are repeated for each of the strata or sub-strata used.

Emissions from deforestation in the year in question are then the sum of conversions from each forest type that occurred in the current year, plus lagged effects from conversions that occurred in any category over the previous 20 years, or for the historical time period being used.

The IPCC methods identified in Table 9: Potential conversions contributing to deforestation and corresponding IPCC Guidance on emissions estimation cover all pools and gases for which Tier 1 methodologies are available and which may be considered the source of significant emissions from deforestation. Advice on the interpretation of the term significant in the REDD+ context in provided in Chapter 2, Section 2.2.3.

Advice on estimating the areas converted (which are the activity data required) and on estimating biomass on the Forest Land prior to conversion (this appears in the IPCC calculations for each potential conversion type as the quantity C_{BEFORE}) is provided in Chapter 5, Section 5.1. In applying the IPCC methods listed in Table 9: Potential conversions contributing to deforestation and corresponding IPCC Guidance on emissions estimation, the MGD process is described in Figure 7: Process flow for estimating deforestation and degradation emissions and advice is as follows:

1. Stratify the national forest area. The suggested basic stratification is into *primary forest*, *modified natural forest* and *planted forest*. Other stratifications may be used, but should enable reporting of these three forest categories to maintain consistency with the FAO Forest Resource Assessment. *Modified natural forest* may be distinguished by coupe and concession records as well as signs of canopy disturbance, detected using remote sensing data showing a shift in spectral reflectance (Margono et.al., 2012; Zhuravleva et.al., 2013), or changes in radar backscatter, or signs of disturbance such as fire scars or logging roads; or by using an NFI. *Primary forests* do not show these signs, although they may have been affected by natural disturbances such as fire or storms. Signs of disturbance should be treated as evidence of modified natural forest unless there is evidence that the disturbance is natural. *Planted forests* are identified using information on planted

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[86] Essentially intact natural forest

[87] Forests with native tree species that have grown naturally where there is evidence of human activities. FRA, 2015 refers to Primary Forest, Other Naturally Regenerated Forest and Planted Forest – see Forest Resources Assessment Working Paper 180

[88] Forests composed of trees established through planting or seeding by human intervention. They include semi-natural plantation forests with indigenous species and plantation forests comprised of exotic species.

areas or concessions, which should be available via the NFMS from plantation companies or local or national authorities, or by using remote sensing data. There should be sub-stratification to capture ecosystems that vary in biomass density within the three main strata, which may also take account of different disturbance levels including the effect of different management types. Stratification should aim to reduce significantly variation in biomass density within a stratum.

2. Obtain average biomass carbon densities for each sub-stratum identified at Step 1:

   a. For *primary forest* and *modified natural forest* the biomass carbon densities are referred to as CB_{PF}, CB_{MNF} respectively. They can be estimated by sampling or from the most recent NFI if there is one with sufficient sampling intensity, plus supplementary sampling if necessary (Appendix B). These possibilities will be referred to collectively as the *sampling*. The sampling should take account of previous impacts such as selective logging (in the case of *modified natural forests*), and natural disturbances, which will have reduced biomass carbon densities. This will require the construction of a map of logging history and prior natural disturbances, using remote sensing and ground observations (e.g. spatial records of prior harvesting, areas impacted by wildfire or cyclone). This should be used for sub-stratification to obtain relatively uniform biomass density. If the sampling comes from an NFI, it may provide merchantable volume data, in which case expansion factors (to convert forest inventory data to total above-ground biomass) and root-to-shoot ratios (to estimate root biomass from estimates of above-ground biomass) are needed to estimate total biomass[89]. Many countries are developing individual tree biomass models based on basic measurements of tree diameter and height. The NFMS should be consulted to ensure that expansion factors, root-to-shoot ratios, carbon per unit of biomass, and other quantities and models are being used consistently across data sources, so that consistent estimates of biomass carbon density are obtained.

   b. For planted forest identified at Step 1 the carbon density can be referred to as the CB_{PlantF}, and should be sub-stratified as necessary. CB_{PlantF}, will depend on the age-class structure of existing planted forests and rate of growth of the species concerned, and the time of harvest and the average delay between harvest and replanting in specific planting cycles. This information should be sought via stakeholder engagement in the NFMS, and can also be supplemented using historical time series of remotely-sensed data.

   c. In applying the IPCC methods referenced in Table 9: Potential conversions contributing to deforestation and corresponding IPCC Guidance on emissions estimation use successively as C_{BEFORE} referred to by IPCC the average values CB_{PF}, CB_{MNF} and CB_{PlantF}, for each relevant sub-stratum of *primary forest*, *modified natural forest* and *planted forest* respectively that is deforested.

3. Use remotely sensed data, plus (if available) NFI data with additional sampling if needed (Appendix B), and information available from the NFMS, to estimate the area converted from sub-stratified forest type j to another land use i. If the area *A(j,i)* is zero then there is no additional contribution to deforested land in the year in question, but there may be contributions to current emissions from non-zero *A(j,i)* values from past years. Use *A(j,i)* values for the current year and past years in the historical period being considered as activity data in the emission estimation method

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[89] For Tier 1, factors are given in 3A.1.10 and 3A.1.8 of the GPG2003 and the corresponding tables in volume 4 of the 2006GL are Table 4.4 (for root-to-shoot ratios) and Table 4.5 (for biomass expansion factors). At higher Tiers country specific data should be used.

referenced in Table 8. As described in the IPCC guidance there is a need to take account of the fate of felled biomass (used either for wood processing or fuel wood, burnt or left to decay *in situ)*.

4. Emissions from each land use change stratum are estimated by multiplying the area deforested by the average change in forest carbon stocks per unit area (ΔCLC) estimated as the difference between the forest carbon stocks per unit area before conversion and the forest carbon stocks per unit area for the new land use after conversion. These are called C_{Before} and C_{After} by IPCC. Default C_{After} values are available in the 2003GL[90]. Uncertainty in biomass carbon densities will lead to correspondingly uncertain emission estimates.

Table 9: Potential conversions contributing to deforestation and corresponding IPCC Guidance on emissions estimation

Index i	Potential conversion	Section of GPG2003 where estimation method is found	Corresponding section in 2006GL
1	Forest to Cropland	3.3.2	Vol 4, section 5.3[91] [92]
2	Forest to Grassland	3.4.2	Vol 4, section 6.3
3	Forest to Wetland	3.5.2	Vol 4, chapter 7[93]
4	Forest to Settlements	3.6.2	Vol 4, section 8.3
5	Forest to Other Land	3.7.2	Vol 4, section 9.3

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[90] Refer to the respective sections of the GPG2003 listed in Table 9: Potential conversions contributing to deforestation and corresponding IPCC Guidance on emissions estimation for default carbon stocks in biomass immediately after conversion (C_{AFTER}; tC ha^{-1}) for the post deforestation land use.

[91] Revised carbon stock and carbon stock change factors for gleysols are provided in chapter 5 of the 2013 IPCC Wetlands Supplement

[92] Revised CO_2 and N_2O emissions factor as well as additional method for off-site CO_2 emissions and for CH_4 emissions are provided in chapter 2 of the 2013 IPCC Wetlands Supplement

[93] Methods for estimating CO_2 and CH_4 emissions from rewetted soils are provided in chapter 3 of the 2013 IPCC Wetlands Supplement

Figure 7: Process flow for estimating deforestation and degradation emissions
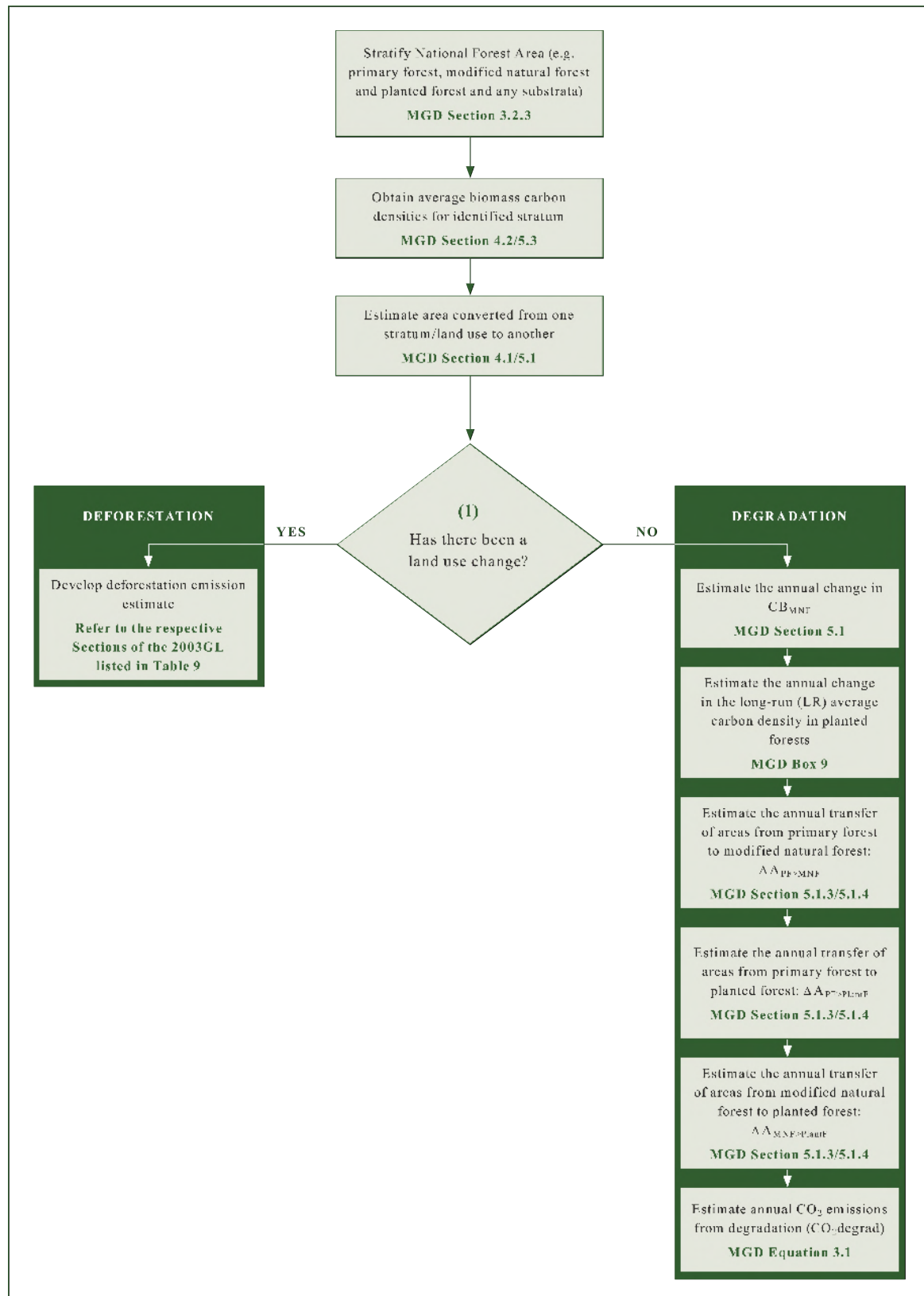
Considerations at the decision points in the tree are as follows:

Decision Point 1: Has there been a land use change?

> A land use change is determined by applying national forest definition thresholds and descriptions in combination with remote sensing and other auxiliary data. A loss of forest cover in one year does not necessarily lead to a deforestation event. Sufficiently frequent time series information combined with ground based information relating to national land use practices within all land uses can greatly assist in distinguishing land use change events from land management activities (i.e. distinguishing deforestation and forest degradation events from temporary unstocked forest lands following timber harvest and lands subject to shifting agriculture).

3.1.2 Estimation of emissions from degradation

There is wide agreement that forest degradation represents long-term loss of forest values, and that temporary loss due to harvest or natural disturbance in sustainably managed forest is not degradation.

For reporting on REDD+, carbon stock is the primary value under consideration, so degradation is interpreted here as the processes leading to long-term loss[94] of carbon without land-use change, otherwise there would be deforestation. Since sustainable management may take other forest values[95] into account, degradation based on long term loss of carbon is not necessarily the same as unsustainable forest management, more broadly defined. In this case any decreases in forest carbon stocks would be estimated through sustainable management of forests, using the method described below in Section 3.1.3. Degradation may occur in any of the forest types considered. In terms of the stratification suggested by the FAO FRA it may start from *primary forest* but does not have to do so. *Modified natural forests*, and *planted forests* are not degrading if the long-run average carbon stock is maintained, or is increasing. Degradation, as interpreted here, occurs in areas where long-run average carbon stock is decreasing, even if temporary increases of carbon stock occur. Regional estimates of degradation have been made in the range 5% to 132% of deforestation emissions (Houghton et al., 2009) and other estimates have been made at 25% and 47% of deforestation emissions (Asner et al., 2005, Asner et al., 2010, FRA, 2015). Forest degradation is likely to be a significant source of GHG emissions globally. Degradation is typified by a change in forest structure and species composition which may result in:

▸ sustained loss of carbon from biomass and dead organic matter (DOM) pools[96];

▸ sustained loss of soil C, especially from peat forests following drainage, fire or exposure after a reduction of canopy density;

▸ sustained increase in emissions of non-carbon dioxide GHGs, especially from fire.

Neither the GPG2003 nor the 2006GL identifies forest degradation by name, but since it occurs on forest land and does not entail deforestation, net GHG emissions associated with it should be estimated using the methodologies described for *Forest Land remaining Forest Land* set out in section 3.2.1 of

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[94] That is to say, increase in the extent of forest strata with lower carbon density, averaged over harvest cycles if appropriate, or declining carbon density within strata as revealed by sampling over time. The application of these ideas is discussed below.

[95] For example biodiversity, fire control, water management or productive capacity

[96] See Table 2: Definitions for carbon pools for pool definitions

the GPG2003[97]. Detecting forest degradation and then estimating the resulting net GHG emissions, requires reliable forest observation techniques, data and resources. Countries should build upon existing systems and capacities where these are available, and integrate degradation measurement systems into their NFMS so that forest degradation is detected and measured in a manner consistent with detection and measurement of other REDD+ activities.

Multiple human-induced and natural processes can cause or contribute to forest degradation, e.g. unsustainable biomass removal from selective logging or fuelwood gathering, over-frequent prescribed burning, or drainage of peat soils. Factors such as climatic stress, wildfire and pest infestation or diseases, though they also occur in forest areas that are not degrading, may also contribute. Degradation will be more apparent where the capacity to regrow is impaired (e.g., following soil erosion, through loss of seed banks, or fragmentation caused by deforestation in adjacent areas).

Degradation may be localised (e.g. where it involves the loss of individual trees or groups of trees) or widespread (e.g., through wildfires covering many thousands of hectares or shortening of harvesting cycles for entire forest types or regions). Patterns vary from selective removal of individual trees or groups of trees, with the latter often leading to the creation of fragments which (unless part of silvicultural strategy leading to regeneration and enhanced growth) are likely to be more susceptible to further degradation. Degradation can take place after a single disturbance event or through gradual processes. Notwithstanding that temporary openings in forest cover can be part of sustainable forest management practices, use of remote sensing may significantly underestimate the extent of degradation (indicated by partial canopy cover reduction) for several reasons, including limited spectral range, the pixel size of the imagery used and the time between image acquisitions over the area of interest. For example, in cases where there is canopy closure after disturbance there may only be a short time period in which degradation can be detected by remote sensing. In other cases, the nature of partial canopy reduction may be below the minimum extent detectable by the satellite. The extent of underestimation can be reduced by using high spatial and temporal resolution data (which is more likely to detect disturbances) and by constraining data analysis so that the transition from MNF to primary forest is not allowed – that is to say once forest has been disturbed, it is assumed to remain so.

In applying the IPCC methods countries may wish to follow the steps set out below. If both forest degradation and deforestation are considered, estimates need to be consistent. In particular, the stratification called for is the same as for deforestation, and steps 1) and 2) below are common with steps 1) and 2) identified above for estimating emissions from deforestation. Step 4) below is not exactly the same as step 3) under deforestation, because the former refers to a long-run average carbon density and the latter to a current value, but the calculation methods are similar and should be consistent. Degradation as estimated by the steps below takes account of long-term reductions of carbon densities due to transitions between forest strata and sub-strata, and within the strata and substrata affected by human activity (i.e. MNF and planted forests). For estimating degradation the steps are:

1. See Step 1 under Deforestation (Section 3.1.1)

2. See Step 2 under Deforestation (Section 3.1.1)

3. Estimate the annual change in CB_{MNF}. Call this quantity B_{MNF}. It may be estimated from repeated NFIs if these exist, by sampling as set out below, by using the gain-loss method as set out in section 3.2.1.1 of GPG2003. It should take account of sub-stratification and factors including forest growth, logging, fuelwood harvest and fire. ΔCB_{MNF} will be positive if ΔCB_{MNF} is increasing, and zero

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[97] Corresponding to volume 4, section 4.2 of 2006GL

or negative otherwise. In order to ensure the terms in the following equation have the correct sign, set factor $f_{MNF} = 0$ if ΔCB_{MNF} is positive or zero and $f_{MNF} = +1$ if ΔCB_{MNF} is negative.

4. Estimate the annual change in the long-run (LR) average carbon density in *planted forests*. The long-run average carbon density is the carbon density averaged across the forest rotation taking account of both growth and harvesting events, and over successive forest rotations. This implies assessment of anticipated forest growth and removals due to harvest especially when there is a significant proportion of newly established planted forest in the planted forest estate. Call this quantity $LRCB_{PlantF}$ and the annual change $\Delta LRCB_{PlantF}$. First estimate $LRCB_{PlantF}$ for the current year, which will depend on the rate of growth of the species concerned, the frequency of harvest and the average delay between harvest and replanting all as anticipated in the current year. This information should be available via the NFMS, from national forest authorities or from commercial operators. Box 9: Estimating long-term average biomass density in planted forests gives an example of the type of the calculations required. Subtract from the current value the value of $LRCB_{PlantF}$ in the previous year to obtain $\Delta LRCB_{PlantF}$. This will be positive if $LRCB_{PlantF}$ is increasing, and zero or negative otherwise. Set $f_{PlantF} = 0$ if $\Delta LRCB_{PlantF}$ is positive or zero and $f_{PlantF} = +1$ if $\Delta LRCB_{PlantF}$ is negative.

5. Using the methods described in Chapter 5 to estimate the annual transfer of areas from primary forest to modified natural forest. Call this quantity $\Delta A_{PF>MNF}$.

6. Using the methods described in Chapter 5 to estimate the annual transfer of areas from primary forest to planted forest. Denote this quantity $\Delta A_{PF>PlantF}$.

7. Using the methods described in Chapter 5 to estimate the annual transfer from modified natural forest to planted forest. Denote this quantity $\Delta A_{MNF>PlantF}$.

8. Estimate annual carbon dioxide emissions from degradation ($CO_{2degrad}$) using the following equation. The significance of the individual terms is described in the steps above and summarized in the Table 10: Terms used in Equation 1:

Equation 1

$$CO_{2degrad} = \left(\frac{44}{12}\right) \begin{pmatrix} \Delta A_{PF>MNF}\left[CB_{PF} - CB_{MNF}\right] + \Delta A_{MNF>PlantF}\left[CB_{MNF} - LRCB_{PlantF}\right] \\ + \Delta A_{PF>PlantF}\left[CB_{PF} - LRCB_{PlantF}\right] + \left(f_{MNF}\right)\left(A_{MNF}\right)\left|\Delta CB_{MNF}\right| \\ + \left(f_{PlantF}\right)\left(A_{PlantF}\right)\left|\Delta LRCB_{PlantF}\right| \end{pmatrix}$$

Inclusion of a quantity in square brackets means that, if negative, the quantity should be treated as zero, so that the corresponding term will not then affect the total emissions from degradation. The f_{PlantF} and f_{MNF} multipliers perform a similar function so that only long-run decreases in carbon density contribute to degradation. Vertical lines mean that the absolute value of the quantity which they enclose should be used. The table below shows the degradation processes to which the five terms on the right hand side of the equation respectively correspond. Since the terms are separately identified, degradation may be disaggregated by process or treated as a sum over processes. For example, if countries wish to distinguish between degradation which may occur in primary and modified natural forest (on the one hand) and that which may occur in planted forest (on the other) then the 5th term in Equation 1 should be removed, and treated separately. The terms in the equation should be sub-divided to take account of sub-stratification.

At Tier 1, GPG2003 assumes that for Forest Land remaining Forest Land, mineral soil, dead wood and litter pools are in equilibrium. If higher Tier methods are being used, national data should enable Equation 1 to be expanded to include them. If organic soils are drained to establish *planted forest*, emissions should be estimated for the corresponding *planted forest* areas as set out in section 3.2.1.3 of GPG2003. Tier 1 carbon dioxide emission/removal factors reported in the IPCC guidance and guidelines for organic soils under different circumstances are summarised in Table 11: Sources of emission/removal factors of organic soils .

Table 10: Terms used in Equation 1

Number of terms in RHS of Equation 1.	Degradation process	Term on the right hand side of Equation 1
0	Multiplies the whole of the right-hand side of the equation and converts from mass of carbon to mass of carbon dioxide	44/12
1	Conversion of primary forest to modified natural forest	$\Delta A_{PF>MNF} [CB_{PF} - CB_{MNF}]$
2	Conversion of modified natural forest to planted forest	$\Delta A_{MNF>PlantF} [CB_{MNF} - LRCB_{PlantF}]$
3	Conversion of primary forest to planted forest	$\Delta A_{PF>PlantF} [CB_{PF} - LRCB_{PlantF}]$
4	Decrease in long-term carbon density of modified natural forest	$(f_{MNF})(A_{MNF}) \Delta CB_{MNF}$
5	Decrease in long-term carbon density of planted forest	$(f_{PlantF})(A_{PlantF})|\Delta LRCB_{PlantF}|$

Table 11: Sources of emission/removal factors of organic soils

Document	Chapter and Section Number	Table Number	Description of default emissions factors
GPG 2003	Chapter 3, section 3.2 – Forest Land	Table 3.2.3	Annual CO_2-C emission factor for drained organic soils in managed forests
GPG 2003	Chapter 3, section 3.3 – Cropland	Table 3.3.5	Annual CO_2-C emission factor for cultivated organic soils
GPG 2003	Chapter 3, section 3.4 – Grassland	Table 3.4.6	Annual CO_2-C emission factor for managed grassland organic soils
2006 GL	Chapter 4 – Forest Land	Table 4.6	Annual CO_2-C and N2O-N emission/removal factors for drained organic soils in managed forests

Document	Chapter and Section Number	Table Number	Description of default emissions factors
2006 GL	Chapter 5 – Cropland	Table 5.6	Annual CO_2-C emissions factor for cultivated organic soils
2006 GL	Chapter 6 - Grassland	Table 6.3	Annual CO_2-C emission/removal factors for drained grassland organic soils
IPCC Supplementary Guidance on Wetlands[98].	Chapter 2	Table 2.1 and 2.2 Tables 2.3 and 2.4 Table 2.7	Annual CO_2-C on-site emissions/removals factor and CO_2-C off-site emission factor for drained organic soils in all land-use categories Annual N_2O-N emissions factor for drained organic soils in forest land CO_2-C and CH_4 emissions/removals factors for peat fires in all land-use categories

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[98] The IPCC Task Force on National Greenhouse Gas Inventories (TFI) has developed additional national-level inventory methodological guidance on wetlands, including default emission factor values, with the aim to fill gaps in the coverage of wetlands and organic soils in the 2006 IPCC Guidelines. This document is called 2013 Supplement to the 2006 IPCC guidelines for National greenhouse gas inventories: Wetlands (the 2013 IPCC Wetlands Supplement).

Box 9: Estimating long-term average biomass density in planted forests

Biomass density (above- and below ground) in a planted forest subject to multiple harvest and subsequent growth will show the saw-tooth pattern illustrated in the figure below. The long-term average carbon density is the carbon density averaged over the initial subsequent rotations. If replanting is immediate this will be a fraction f_1 of the above-ground biomass density at the time of each harvest. The fraction f_1 is commonly about 0.5. If there is significant delay (say δt) between harvest at the time of replanting and the time from replanting to harvest is t_1 then the long-run average biomass density is $P.(f_1.(t_1/(t_1+\delta t))+r)$ where P is the above-ground biomass density at the time of harvest and r is the root-to-shoot ratio. P and r will depend on species, site conditions and management inputs. If there are 0.5 tonnes of carbon per tonne of biomass then $LRCB_{PlantF}$ = (0.5) $P.(f_1.(t_1/(t_1+\delta t))+r)$. The basic information required from stakeholders is growth rates and the timing and nature (biomass removed) of harvest, and whether there are significant delays in replanting. Better values can be obtained using growth models which can take account of the effect of disturbance on r. Other carbon pools are taken into account at higher Tiers.
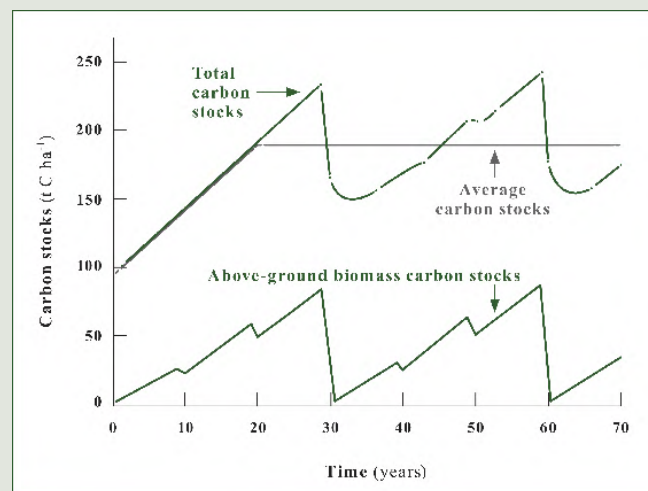
3.1.3   Sustainable management of forests, enhancement of forest carbon stocks (within existing forest), and conservation of forest carbon stocks

These activities are likely to be associated with specific national and regional policies, which may be linked to particular geographical areas, consistent with national strategies for sustainable management, implying need for appropriate sub-stratifications. Recognising that countries will have national forest definitions, there seems wide agreement that *sustainable management of forests* aims to maintain and enhance forest values[99]. This does not necessarily mean maintaining the carbon stocks initially present

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[99] Although the language refers to sustainable forest management rather than sustainable management of forests, the UN has recognised that sustainable forest management, as a dynamic and evolving concept, aims to maintain and enhance the economic, social and environmental values of all types of forests, for the benefit of present and future generations (Non-legally binding instrument on all types of forests, adopted by the UN General Assembly 22 Oct 2007)

in primary or modified natural forests. For example, average biomass carbon stocks are always less in harvested forests than in equivalent areas of forests that are not subject to harvest, but in a sustainably managed production forest carbon stocks would not decline over time when averaged over harvesting cycles (thus reflecting sustained productive capacity). *Conservation of forest carbon stocks* aims to maintain carbon stocks. *Enhancement of forest carbon stocks* aims to increase carbon stocks, which could be within an existing forest area, or by converting another land use to forest. This second possibility is methodologically distinct because it entails land-use change, and is dealt with separately below. *Enhancement of forest carbon stocks (within an existing forest), conservation of forest carbon stocks,* and *sustainable management of forests* would all occur within existing forest areas that remain forest areas. Therefore, as with degradation, GHG emissions and removals associated with them should be estimated using the methodologies described for Forest Land remaining Forest Land set out in section 3.2.1 of GPG2003 [(100)]. These methods address above- and below-ground biomass, litter, dead wood and soil organic matter and associated emissions of non-carbon dioxide GHGs. Since these activities are generally intended to maintain or increase forest carbon stocks, they are the reverse of degradation, and sometimes the same activity can lead to degradation or the reverse, depending on the intensity, an example being harvesting. Estimation of carbon change for the above activities should therefore be consistent with estimation for degradation. Therefore to estimate emissions and removals from *sustainable management of forests, enhancement of forest carbon stocks (within an existing forest), and conservation of forest carbon stocks*, countries are advised to follow steps 1 to 9 set out above for degradation, in the following way:

▸ Within the stratified areas, for example *primary forest*, *modified natural forest* and *planted forest*, if there are particular areas subject to sustainable management activities, use remote sensing data in combination with information from national forestry authorities to identify these as sub-strata. This step will be unnecessary if all the strata are subject to sustainable management.

▸ The equation for estimating emissions and removals from these activities becomes:

Equation 2

$$CO_{2\,sust} = \left(\frac{44}{12}\right)\left(\begin{array}{l}\Delta A_{PF>MNF}\left(CB_{PF} - CB_{MNF}\right) + \Delta A_{MNF>PlantF}\left(CB_{MNF} - LRCB_{PlantF}\right) \\ + \Delta A_{PF>PlantF}\left(CB_{PF} - LRCB_{PlantF}\right) - A_{MNF}\left(\Delta CB_{MNF}\right) - A_{PlantF}\left(\Delta LRCB_{PlantF}\right)\end{array}\right)$$

This version of the equation assumes that all the forest remaining forest is subject to the activities sustainable management of forests, enhancement of forest carbon stocks (within an existing forest), and conservation of forest carbon stocks; and all terms contribute to the total irrespective of sign. Equation 2 is arranged so that CO_{2sust} will be negative (corresponding to a removal) if carbon stocks are increasing. Equation 2 assumes that primary forest can become modified natural forest or plantation forest, and that modified natural forest can become planted forest, but that the reverse transitions do not occur. Table 12: Terms used in Equation 2 shows the processes to which the five terms on the right hand side of Equation 2 respectively correspond. Since the terms are separately identified, emissions and removals from these activities may be disaggregated by process or treated as a sum over the processes involved.

[(100)] Corresponding to volume 4, section 4.2 of 2006GL

If a transition occurs in a partitioned forest type, the carbon densities to use are those which correspond to the transition being made. If primary forest is successfully conserved then $\Delta A_{PF>MNF}$ and $\Delta A_{PF>PlantF}$ will both be zero.

If forest degradation and the sustainable activities are both present, then to avoid double-counting:

▸ if emissions from degradation and the sustainable activities are to be separately identified, degradation should be estimated using Equation 1 and the sustainable activities then estimated as the difference between Equation 1 and Equation 2. If Equation 1 has been disaggregated in some way, e.g. by treating planted forests separately, then Equation 2 should be disaggregated in the same way.

▸ if all degradation and the sustainable activities are to be estimated together only Equation 2 should be applied. Since there are no sign restrictions in Equation 2 any degradation which occurs within activities defined as *sustainable management of forests, enhancement of forest carbon stocks (within an existing forest), and conservation of forest carbon stocks* will be included in the emissions estimate.

As in the case of degradation, at Tier 1, GPG2003 assumes that for Forest Land remaining Forest Land, mineral soil, dead wood and litter pools are in equilibrium. If higher Tier methods are being used, national data should enable Equation 2 to be expanded to include them. If organic soils are drained to establish *planted forest*, emissions should be estimated for the corresponding *planted forest* areas as set out in section 3.2.1.3 of GPG2003. Tier 1 carbon dioxide emission/removal factors reported in the IPCC guidance and guidelines for organic soils under different circumstances are summarised in Table 11: Sources of emission/removal factors of organic soils .

Table 12: Terms used in Equation 2

Number of term on RHS of Equation 2	Process	Term on the right hand side of Equation 2
0	Multiplies the whole of the right-hand side of the equation and converts from mass of carbon to mass of carbon dioxide	44/12
1	Conversion of primary forest to modified natural	$\Delta A_{PF>MNF}(CB_{PF} - CB_{MNF})$
2	Conversion of modified natural forest to planted forest	$\Delta A_{MNF>PlantF}(CB_{MNF} - LRCB_{PlantF})$
3	Conversion of primary forest to planted forest	$\Delta A_{PF>PlantF}(CB_{PF} - LRCB_{PlantF})$
4	Change in long term carbon density of modified natural forest	$A_{MNF}(\Delta CB_{MNF})$
5	Change in long term carbon density of planted forest	$A_{PlantF}(\Delta LRCB_{PlantF})$

3.1.4 Enhancement of forest carbon stocks (afforestation of land not previously forest, reforestation of land previously converted from forest to another land use)

In addition to enhancement within existing forests, forest carbon stocks can be enhanced by establishing forests on land which was not previously forest, or which had earlier been converted from forest to another land use. Forest establishment on such land will result in carbon accumulation in biomass, though initially the loss of soil carbon due to disturbance of carbon stocks in mineral soils may exceed the biomass accumulation; and if organic soil has been drained, this loss will continue as long as the drainage continues. Accumulation of biomass will follow a sigmoid curve, with rates varying with species, site growing conditions and age. Harvest will interrupt the sigmoid accumulation of biomass (with disturbance emissions) with growth resuming again after replanting. This produces the characteristic saw-tooth curve illustrated in Box 9: Estimating long-term average biomass density in planted forests. Harvesting with replanting is part of a forest management cycle and does not constitute deforestation, because the land use does not change. Neither is it degradation within forest land use if the average carbon stock is maintained in the long term (Section 3.1.2). Planted forests established for environmental values will not necessarily be harvested, and if they are not, the initial sigmoid will proceed to saturation at the carbon carrying capacity of forest on the land concerned, and there will be no saw-tooth pattern. Consistent with the *GPG2003 and the 2006GL*, emissions and removals on unmanaged[101] land are not included in GHG inventories so it is assumed that forest expansion on unmanaged land will not count towards this activity. Consistent with the agreed safeguards[102], REDD+ actions should not be used for conversion of natural forest.

Since this entails a conversion of another land use *to* forest it corresponds directly to section 3.2.2 of GPG2003, *Land Converted to Forest Land*, corresponding to volume 4, section 4.3 of 2006GL. In applying the IPCC methodology countries should:

1. Via the NFMS, collect information on forest establishment on lands not previously used as forest, or on lands which were once used as forest but have been converted to another land use. Information may be available from stakeholders, government departments or forestry authorities (all of whom should be represented on the NFMS) on tracking concessions and planting permits. Remote sensing may not always be a useful data source for this step, because forests in the early stage of growth are not easily distinguished by remote sensing. It may be possible to detect signs of preparation and planting work and this can be used as supporting information. The information sought should include type of forest established, planting date, and if possible a management plan.

2. As the planted forest grows following establishment, use remotely sensed data to confirm the forest areas and timing of harvest activities and resolve any differences with the information obtained under 1). This will improve the accuracy of results.

3. Utilize yield tables or growth curves in the generation of changes in carbon density through time on afforested/reforested lands. In the absence of such annual biomass estimates, averages may be used as an interim measure, however their use can introduce bias especially in early years of forest establishment or where actual growth rates are not representative of the average (i.e. where the percentage survival is known to be low). An assessment of such bias should be conducted and transparently reported. Priority improvements to reduce bias should also be identified.

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[101] See section 1, GPG2003 for a discussion of forest definitions including managed and unmanaged forest.

[102] See paragraph 2(e) of Appendix 1 to the Cancun Agreements contained in decision 1/CP.16.

4. In making national estimates, emissions and removals associated with this activity should be included with those from sustainable management of forests, enhancement of forest carbon stocks (within an existing forest), and conservation of forest carbon stocks.

3.1.5 Conversion of natural forest

The Cancun Agreements list *conversion of natural forest* under safeguards provisions, not as a REDD+ activity. The Agreements specify[103] the need to *promote and support* safeguards ... *consistent with the conservation of natural forests and biological diversity, ensuring that [REDD+ activities] are not used for the conversion of natural forests, but are instead used to incentivize the protection and conservation of natural forests and their ecosystem services, and to enhance other social and environmental benefits.* The annual area converted can be calculated as the sum $\Sigma_{i=1,5}\, A_{(1,i)}$ where j=1 is taken to be the index for primary forest at step 5 above under deforestation emissions estimation, *plus* the transfer rates from modified natural forest to planted forest and from primary to planted forest, $\Delta A_{MNF>PlantF}$ and $\Delta A_{PF>PlantF}$ estimated respectively at steps 5 and 6 under degradation emissions estimation. This covers conversion of natural forest to non-forest land uses, and to other forest types. The emissions associated with these transfers can be estimated from the application of the IPCC methods identified above to these transferred areas.

3.2 Integration frameworks for estimating emission and removals

Developing systems for reporting greenhouse gas emissions and removals requires combination of data from different sources, with data gaps filled through assumptions and expert judgement where necessary (Box 10: Data, assumptions, models, tools and emissions estimation). Tools to facilitate this are known as integration frameworks. Integration frameworks that are designed to simulate the impacts of human activities on future carbon stock changes can also support development of scenarios relevant to policy analyses. Integration frameworks can simplify reporting by automatically assigning land uses and emissions to the required classes based on rules set by the user, consistent with national definitions.

Ideally, an integration framework should be scalable and apply to forest stands, projects, regions or countries. It should also be able to start with simple, best available data, and be improved progressively; at each stage meeting IPCC good practice requirements of neither under- nor over-estimation so far as can be judged, and reducing uncertainties as far as is practicable.

Integration frameworks require knowledge of[104]:

1. initial land cover condition of the landscape (i.e. forest, non-forest or other land cover classes)

2. drivers of change (activity data on human and natural disturbances), and estimates of subsequent land use (where a land use change has occurred)

3. initial condition of the forest and rates of forest growth

4. rate of carbon loss from decomposition and transfer between pools (for dead organic matter, soils, wood products as required)

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[103] See paragraph 2(e) of Appendix 1 to the Cancun Agreements contained in decision 1/CP.16.

[104] The points listed are most relevant for integration frameworks based on gain-loss approaches.

These data, in particular the data on land cover, land cover change and the agents of change are increasingly obtained from remote sensing. These can greatly assist in describing the history of land-cover changes that drive emissions and removals (Chapter 5, Section 5.1). The further back in time these data go on a consistent basis (Box 23: Time series analysis of earth observations for monitoring of activity data), the more reliable and useful they are as the inputs to the integration tools.

The analysis of the impacts of future REDD+ (or forest management scenarios more generally) can be undertaken with integration frameworks (e.g. CBM-CFS3, FullCAM) that can use scenarios of future activity data to extend historical time series activity data. For example, if the past rate of deforestation activity is estimated from remote sensing observations, this rate can be extended into the future as a baseline (e.g. the average rate of deforestation over the past N years) and be compared against one or more scenarios showing the impacts of reducing deforestation rates by X or Y% per year (e.g. Kurz et al., 2016). Provided the socio-economic drivers can be identified and quantified and the relationship between them understood, it is easier to extend time series of activity data in integration frameworks that use spatially-referenced activity data. Extending the observed time series of activity data with projections about alternate future management regimes in Canada's National Forest Carbon Monitoring, Accounting and Reporting System have allowed for the evaluation of various climate change mitigation strategies (Smyth et al., 2014).

Box 10: Data, assumptions, models, tools and emissions estimation

All emissions estimation relies on measurement data, assumptions, models and other tools. Understanding each of these components is helpful when developing MRV systems.

Data: Data can be divided into measurement data (such as forest inventory measurements) and derived data (such as biomass estimates derived from the base measurements such as diameter at breast height). Derived data require the application of models such as volume and taper equations to estimate tree volumes or allometric models to estimate biomass. Measurement data have errors associated with the measurement and derived data have errors associated with the model in addition to measurement errors.

Assumptions: To convert input data to numbers that can be used in emissions estimation requires assumptions. For example, emissions factors assume that growth occurs at the same rate between two points in time, while growth curves assume that the forest is following a non-linear growth pattern. These assumptions affect the accuracy of the results at any point in time and cannot be improved merely by increasing the statistical accuracy of an individual point in time.

Models: All systems rely on models of various complexity and all models rely upon data and assumptions. Generally, moving from simple assumptions and models, such as linear growth curves in Tier 1 and 2 emissions factor methods, to more realistic s-curve forest growth and yield assumptions in Tier 3 methods leads to greater accuracy in emissions estimates through time (Figure 10: Distribution of Landsat scenes with less than 20% cloud cover archived for Bolivia). The increase in complexity between Tier 2 and 3 can be small in the case of empirical growth curves (which are commonly applied in forestry operations worldwide), or large if implementing more complex, physiological models. Models can be brought together through the use of integration tools.

Integration tools: Integration tools combine multiple streams of information, most commonly spatial data, such as from remote sensing, and forest inventory data from ground and plot measurements with models. Models can help obtain estimates for pools that are difficult to measure (e.g. soils), and to extrapolate measurements obtained from plots across space and time. Tools may range from simple excel sheets (e.g. EXACT) through to stand-alone executables (e.g. ALU) and detailed analytical systems (e.g. CBM-CFS3, FullCAM, and the new system under development: FLINT). Some of these tools may have models and assumptions built into them, but most are flexible and allow for different data and assumptions to be used and modified.

The figure below presents a comparison of an emissions/removals factor model and a typical growth curve. Both predict similar biomass at age 100, but the pattern is different, leading to potential bias in estimates of carbon accumulation rates in biomass. Both models are simplifications of the real biomass accumulation rate which also varies over time as a function of climatic and other environmental conditions. This can have a significant impact over short periods.
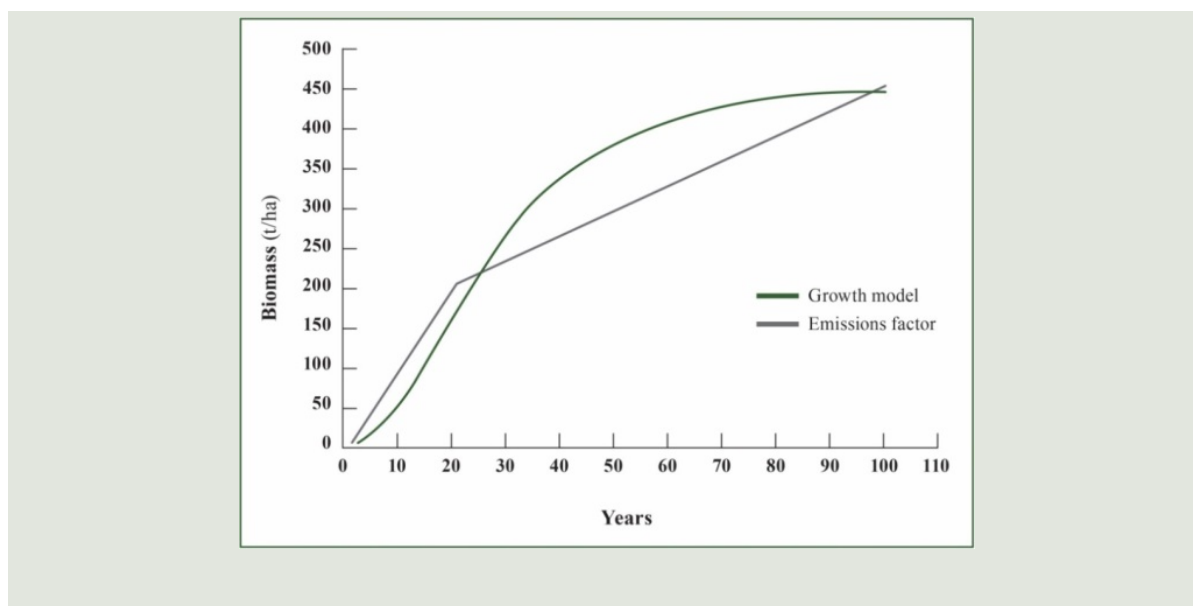
3.2.1 Selecting an integration framework

Selecting an integration framework for MRV requires consideration of practical and scientific issues including:

▸ national and international reporting requirements;

▸ data availability;

▸ technical means and capacity;

▸ standards by which the system and its outputs will be assessed;

▸ availability of integration frameworks (also referred to as integration tools) and the expertise to implement these within the country;

▸ cost effectiveness.

There are two main methods for integration remote sensing and ground-based observations:

1. The activity data x emission/removal factor frameworks (representative of Tier 1 or Tier 2 methods).

2. Fully Integrated frameworks, with two sub-cases:

   a. Spatially-referenced models (representative of Tier 3, Approach 2/3 methods)

   b. The spatially-explicit methods (representative of Tier 3, Approach 3 methods) which track individual units of land (polygons or pixels).

All these methods have been used by countries in developing land sector GHG estimates and, when applied correctly, all comply with UNFCCC rules and IPCC guidelines. However, the accuracy of estimates obtained can vary greatly. Tier 3 approaches may be more accurate or precise because they do not have to deploy simplifying assumptions inherent in emission/removal factor based approaches, and because they may be able to accommodate more refined stratification of forest conditions (forest types, ecological and climate conditions, age classes, disturbance and management history, etc.) although the complexity may increase and transparency decrease as a consequence.

Methods of integration are not mutually exclusive. Most countries currently use a combination of integration methods depending on the nature of forest land use, and availability of data. It is sensible to implement a national system progressively within a single integration framework. This makes it possible initially to implement simpler methods to meet short-term needs, without sacrificing the longer-term goals. For example, integration framework can initially represent only a small number of forest strata with the associated small number of growth curves. As more data become available through implementation of improvement plans for identified significant or key categories (Chapter 2, Section 2.2.3) the spatial scope of the integration framework can be expanded. Well-designed frameworks should be able to accommodate increase in estimation complexity and data richness.

3.2.1.1   Activity data x emission/removal factor frameworks

In general activity data x emission/removal factor methods[105] are more suitable in landscapes with few sequential changes through time. As the number of potential changes and classes increases, the efficiency of using this approach decreases and the potential for bias increases. The cost of developing numerous EFs can eventually become greater than the cost of developing a Tier 3 system to account for the many factors affecting emissions and removals such as disturbance type, disturbance intensity, other management actions and site and climate conditions. Emission/removal factor based systems are challenged by repeated transitions between land-use categories. By default the IPCC guidelines assume a 20-year transition period but if subsequent land-use changes occur within this period, the emission/removal factor based systems typically do not have appropriate emission/removal factors to accommodate multiple transitions. The IPCC does not provide explicit guidance on how to apply emission/removal factors when there are multiple changes within the transition period. Though logically if a linearized 20 year transition to a known after-change carbon density[106] is interrupted, and a new land use or management regime established with a new after-change carbon density, the emissions and removals from the land in question could be calculated by keeping track of the land in question, and using an emission/removal factor equal to the difference between the partially completed carbon density change, and the new after change carbon density, annualized over 20 years. This is an example of a rule referred to in Box 5: Land use and REDD+ activities. A more sophisticated approach would replace the linearized change with an exponential transition with empirically established time constants for carbon loss or gain.

In countries where there are multiple clearing and regrowth cycles (shifting agriculture being an example) it will be necessary to not only estimate emissions from the initial clearing, but to also estimate the removal and subsequent future emissions during repeated cycles of clearing and regrowth. Unless a manageable number of statistically representative strata can be identified, representing such patterns of growth rates can become complex, especially where there are other factors involved such as multiple forest types and types of disturbance (i.e. commercial timber harvest or shifting cultivation). Complex patterns of degradation or other multiple changes on single units of land, such as degradation prior to deforestation, can also be difficult to account for using simpler tools due to the sheer number of possible permutations. The complexity increases as more strata and disturbance types need to be included. Even if applying Tier 1 or 2 approaches it may be worth using the more advanced, fully integrated tools to manage the large number of transitions and resulting combination of stock changes.

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[105] These method are referred to as Tier 1 and Tier 2 methods

[106] For example in the case of mineral soils use calculated by use of reference carbon density under native vegetation and application of the relative carbon stock change management factors.

3.2.1.2 Fully integrated frameworks

Fully integrated frameworks[107] aim to estimate emissions using knowledge of site-specific conditions and drivers of change such as management, natural disturbances, and land-use changes. These systems are more detailed than the activity data x emission/removal factor methods, but have significant advantages including:

- more efficient integration of remote sensing data with emissions estimation equations

- a greater ability to analyse the effects of management on emissions

- ability to project emissions estimates to enable scenario analyses

- ability to expand as necessary through ongoing development

- more automated methods of data checking and QA/QC, including preventing double counting of lands

These frameworks are generally considered Tier 3 but can also be applied with Tier 1 and Tier 2 methods. In such cases the integration framework can assist to increase the overall accuracy of the system by accommodating greater information on the history of land use. The frameworks can more easily allow Tier 1 and Tier 2 methods to be applied to Approach 3 data.

Fully integrated Tier 3 frameworks utilise mass-balance models that capture all major carbon pools and movements between them (Box 11: Mass Balance Approaches). These models seek to better represent changes in carbon stock due to activities not easily covered by emissions/removals factors (such as partial harvests or fire), can allow for the tracking of the fate of material (for example logging slash) and can be expanded to other pools such as debris and soil carbon. Fully integrated frameworks usually include tools to estimate the fate of harvested material and to estimate C stocks and emissions in products manufactured from harvested wood. A number of approaches to estimating the fate of carbon in harvested wood products exist (Brunet-Navarro et al., 2016, IPCC GPG2003[108],2006GL[109], 2013 KP Supplement[110]).

Fully integrated Tier 3 methods can also use remote sensing not only to develop activity data, but also use these data to help reduce bias and improve the accuracy of the results. For example, by tracking individual units of land through time, it is possible to determine the history of an area, and hence more accurately predict its current state. Fully integrated frameworks aim to bring all the core activity data and emissions estimation processes together. They can provide an efficient processing platform to deal

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[107] Fully integrated frameworks can support Tier 1, Tier 2 or Tier 3 methods

[108] See appendix 3.a.1 of GPG2003

[109] See volume 4, chapter 12 of 2006GL

[110] See 2013 KP Supplement section 2.8

with complex land use histories. The results and ability of the frameworks are constrained by the data and methods used in them, but they can have significant advantages over simpler tools including:

- ability to represent accurately key flows of carbon (e.g. growth and decay from natural processes, harvesting, fire and insect disturbance)

- ability to be parameterised using available or readily collectable data

- incorporate checks and balances that prevent unrealistic results

- incorporate tests to ensure that mass-balance is guaranteed at all steps through the model (i.e. the inputs and outputs (flows) should always match the carbon stock change (mass balance)

There are currently no operational examples of full process-based approaches due to the amount of data required to calibrate and operate such models, the often-unconstrained nature of their outputs, and the often- divergent estimates of the impacts of environmental drivers on emissions and removals (Huntzinger et al., 2012).

Current operational Tier 3 integration frameworks use a variety of models from fully empirical modelling (Kurz et al., 2009) to hybrids of process and empirical models (Brack et al., 2006; Waterworth & Richards, 2008). The methodological choice depends on availability of existing data (for example, remote sensing, mapping or national forest inventories), required outputs and cost.

Box 11: Mass Balance Approaches

In mass-balance approaches (also known as 'book-keeping' or 'conservation of mass' approaches), stocks and stock changes in each pool are based on transfers between pools using knowledge of the carbon cycle as depicted in the diagram below. Mass-balance systems can be used for estimating annual emissions/removals and tracking emissions/removals due to specific events such as harvesting or fire.

To be applied in national inventory systems, fully integrated, mass balance approaches need at least:

- be able ability to represent accurately key flows of carbon, for example flows from natural processes (growth and decay), harvesting, fire, insect attack

- be parameterised using available or readily collectable data

- have checks and balances to prevent unrealistic results

- have tests to ensure that mass-balance is guaranteed at all steps through the model

- have inputs and outputs (flows) that match the carbon stock change.
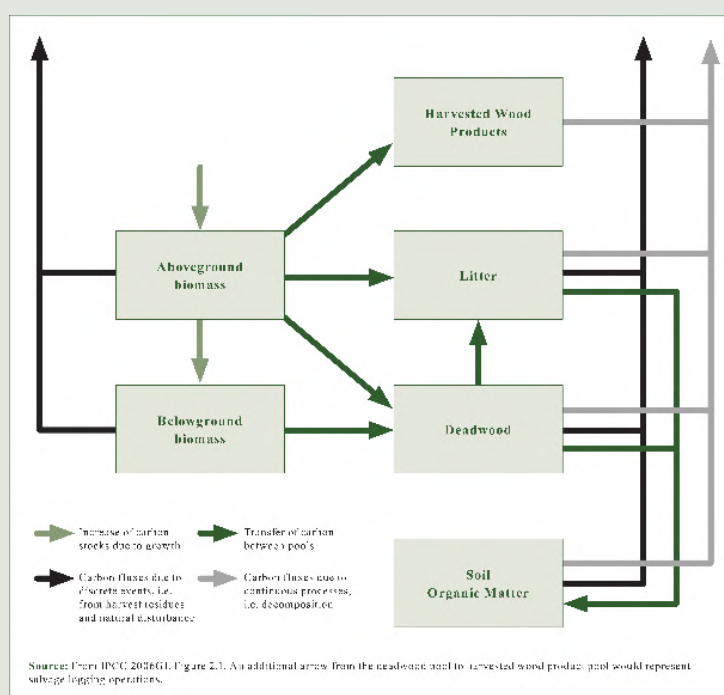
Source: From IPCC 2006GL Figure 2.1. An additional arrow from the deadwood pool to harvested wood product pool would represent salvage logging operations.

3.2.1.3 Spatially explicit methods

Spatially-referenced models track individual changes within the landscape. They are particularly useful in dynamic landscapes where there are multiple changes in land use and management through time. This is commonly the case in developing countries, but also occurs in countries such as Australia and Canada which use these models.

Three methods are relevant: stand-level models, pixel-based or a combination of both.

▸ **Stand level models** are similar to the methods applied by many forestry agencies to assess timber growing stock. In this configuration, emissions and removal estimates are developed for each stand and the results summed for the entire forest area. Stand-level models are appropriate to countries with detailed existing mapping of stands and harvested blocks along with details on activities such as harvest and replanting records. This mapping is not traditionally derived from satellite remote sensing, but remote sensing can be used to determine stand boundaries. These methods are suited to situations where there is a good history of forest management. They also allow for more advanced methods of developing emissions projections based on proposed changes in harvesting or predicted future natural disturbance probabilities. They are less useful for countries with a limited history of stand mapping and large amounts of land-use change.

▸ **Pixel based models** track individual pixels as land units, rather than stands, although pixels with similar attributes can be combined to increase efficiencies (see below). Pixel-based models aim to utilise the full strength of historical time series remote sensing observations and are suited to situations of multiple changes in land use or cover through time (for example, shifting agriculture). They are also suited for deforestation and where there is little or no recorded history for forestry activities that could be applied in stand-based models. Pixel-based models utilise both spatial and non-spatial data to parameterise the model for each pixel. This is achieved by integration the remote sensing information with other spatial datasets (such as climate, productivity, soil type, forest type) and spatially-referenced databases that provide species specific and management information. Summing the results of all the (relevant) pixels creates the estimate for the region or nation.

▸ **Combined pixel and stand-based methods**. It is theoretically possible to develop a method that combines the pixel and stand based methods to remove the potential weaknesses of each approach. So far this has not been attempted in an operational system. There are some current efforts to develop tools that can do this, but these remain prototypes.

3.2.1.4   Spatially referenced methods

Spatially-referenced methods use information about land use and activities within geographic boundaries. The exact location of the forest and activity that drives emissions and removals within the land area is unknown, although the geographic boundaries of land can be determined by administrative or ecological considerations. For example, it is possible to determine through sampling (remote sensing or forest inventory) the amount of land within a region that is covered by a certain forest type. Sampling will not provide information on the exact location of these forests, but if well-designed and sufficient it can provide an accurate and precise estimate of the total area. Ongoing sampling can be used to determine area change. The area and area change can then be used in integration frameworks to estimate emissions.

Spatially-referenced methods use regionally or species-specific management data and forest growth curves derived from research sites or forest inventory data. Spatially-referenced methods are suited for developing projections as the exact location of projected changes is not required, and also to situations where a sample-based remote sensing program is used to develop activity data. In such cases the samples can be used to develop activity data that can be applied to the appropriate models.

3.2.2 Activity data x emission/removal factor tools

There are three main tools that have been developed around the activity data x emission/removal factor method[111]: EXACT, ALU and IPCC tools. The IPCC and ALU tools have gained widespread use and are being continually updated to ensure compliance with good practice. Both generate outputs that meet the requirements of the 2006GL.

Tabulated activity data generated from remote sensing observations can be entered into all of these tools. The ALU tool (Box 12: Agriculture and land use greenhouse gas inventory (ALU) software) is also capable of using GIS data to develop spatially-explicit estimates of emissions, but is not able to support the more sophisticated pixel or stand-based approaches and cannot easily track multiple changes in land use on a single land unit.

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[111] These tools typically support Tier 1, and in some cases, Tier 2 methods

Box 12: Agriculture and land use greenhouse gas inventory (ALU) software

The agriculture and land use greenhouse gas inventory (ALU) software guides an inventory compiler through the process of estimating greenhouse gas emissions and removals related to agricultural and forestry activities. The software simplifies the process of conducting the inventory by dividing the inventory analysis into steps to facilitate the compilation of activity data, assignment of emission/removal factors and completion of the calculations. The software also has internal checks to ensure data integrity. Many governments also have an interest in mitigating greenhouse gas emissions from agriculture and forestry. Determining mitigation potential requires an understanding of both current emission trends and the influence of alternative land use and management practices on future emissions. The ALU software program is designed to support an evaluation of mitigation potentials using the inventory data as a baseline for projecting emission trends associated with management alternatives.

ALU can be used to estimate emissions and removals associated with biomass C stocks, soil C stocks, soil nitrous oxide emissions, rice methane emissions, enteric methane emissions, manure methane and nitrous oxide emissions, as well as non-CO_2 GHG emissions from biomass burning. Methods are based on IPCC guidelines.

Two versions of the ALU software are available:

  a. Version 5.0 based on the methods in the 2006GL

  b. Version 4.5 based on the methods in the revised 96GL and refined in the 2000 and GPG2003.

The software has several innovative features including:

  ▸ Accommodates Tier 1 and 2 methods as defined by the IPCC

  ▸ Allows compilers to integrate GIS spatial data along with national statistics on agriculture and forestry

  ▸ Designed to produce a consistent and complete representation of land use for inventory assessment

  ▸ Can develop an enhanced characterization for livestock

  ▸ Has explicit quality control and quality assurance steps

  ▸ Provides a long-term archive of data and results in digital format

  ▸ Generates emission reports that can be included in communications with interested parties.

3.2.3 Fully integrated tools

Several countries utilise fully integrated tools for estimating emissions from forestlands[112]. Descriptive case studies are provided in Appendix C. There are currently two operational fully integrated tools used for reporting to the UNFCCC: the Full Carbon Accounting Model of Australia (FullCAM) and the Carbon Budget Model for the Canadian Forest Sector (CBM-CFS3) (Box 13: High level description of fully integrated tools). Both have been used to develop multiple inventories in their respective countries

[112] These tools support Tier 1, Tier2 and Tier 3 methods.

and have also been applied in other countries[113]. For example, the CBM-CFS3 has been applied by the Joint Research Centre of the EU to 26 EU countries providing a single consistent methodology to compare country-level submissions (Pilli et al., 2016). Both tools are freely available and, in the case of the CBM-CFS3, are backed with support including frequent training courses and email help systems.

Both FullCAM and the CBM-CFS3 are mass-balance frameworks that utilise a mix of empirical and process models to estimate emissions from all pools. The advantage of these frameworks is that all of the data (e.g., growth curves, emissions factors, model calibrations, activity data) are held externally to the systems and only drawn into the framework as required. This allows for data to be easily updated and for the development of projections (Stinson et al., 2011, Smyth et al., 2014, Australian Government, 2011).

[113] Examples are described in more detail in Appendix C

Box 13: High level description of fully integrated tools

CBM-CFS3*:* The CBM-CFS3 is an example of a flexible integration framework that can implement both spatially-referenced (Stinson et al., 2011, Kurz et al, 2008) and spatially-explicit approaches (both polygon (Trofymow et al., 2008) and pixel-based (Mascorro et al., 2015)) to simulate forest carbon dynamics as affected by forest growth, mortality, natural disturbances, forest management and land-use change. Moreover, the model can simulate a single stand, a region or several hundred million hectares of forests. Depending on available data, it can be scaled up from representing a small number of forest strata to representing many thousands of forest strata. The model has been applied in Canada, 26 European Union countries, Russia, Korea, Mexico, China and other regions. Because the model was developed more than 15 years ago, the main constraints in the toolbox arise from software and hardware limitations that make it difficult and impractical to scale the model to pixel-based approaches with millions of pixels. While some tools have been developed as interim solutions, work is under way to implement the scientific modules of the CBM-CFS3 on a new platform (FLINT).

FullCAM: The Full Carbon Accounting Model is another example of a flexible integration framework. Similar to the CBM-CFS3 it can operate using spatially-referenced or spatially-explicit approaches, but its main strength is running pixel-based systems. FullCAM can also model emissions from the entire land sector (both forest and non-forest land uses). FullCAM models both biological and management processes which affect carbon pools and transfers between pools in forest and agricultural systems. The exchanges of carbon, loss and uptake between the terrestrial biological system and the atmosphere are accounted for in the full, closed cycle mass balance model which includes all biomass, litter and soil pools (Waterworth & Richards 2008). Analysis and reporting includes all carbon pools (biomass, dead organic matter and soil), greenhouse gases (carbon dioxide, methane and nitrous oxide).

FullCAM has been supporting the production of the Australian national greenhouse gas inventory since 2005. While drawing on pre-existing constituent models (like CamFOR and Roth-C), there were elements in the initial design that were Australian-specific and not designed with a broader international purpose in mind. Consequently, like all systems, implementation of country-specific models would require detailed support. On the other hand, much of the system is generic and Australian-specific elements are in the process of being standardised to ensure broader application.

FLINT*:* The Full Lands Integration Tool (FLINT) is a second generation integration tool currently under development through collaboration between Kenya, Australia and Canada. The need for FLINT arose as there were no existing integration tools that could meet all the needs of the Systems for Land-based Emissions in Kenya (SLEEK). Due to the cost of developing an integration tool it was decided to design the FLINT as a generic framework. This will allow other countries to easily use the same tool, hence reducing costs for others in the future. This will also increase transparency, comparability and validation of reported estimates.

The FLINT incorporates the lessons from the teams that developed the CBM-CFS3 and FullCAM. The core design features are:

1. Full-mass balance framework that can meet all IPCC requirements

2. A customisable platform to meet national policy and reporting requirements

3. Modular system design that allows countries to easily add their own carbon modules

4. Ability to run in spatially explicit and spatially referenced modes

5. Ability to produce reports of past emissions and removals as well as projections in support of policy analyses such as REDD+ or mitigation scenarios

6. Increased simulation speeds and ability to run on computer clusters and cloud frameworks, which will facilitate the use of tools in countries with limited computing resources

7. Access to global data sets such as remote sensing time-series and climate data layers which can be used to augment regional and national data

8. Flexible methods of representing all land uses.

FLINT is currently operating as a prototype, with initial full runs for the entire Kenyan land sector to occur in mid-2106. Canada has implemented most CBM-CFS modules on the FLINT platform and has verified the new module estimates against the CBM-CFS3. FLINT will be open source with a proposed management structure that will allow countries using the tool to make requests for enhancements and support, pending resource availability.

3.2.4 Practical considerations in choosing an integration tool

Developing an integration tool, even for the simpler activity data x emission/removal factor method, requires significant technical expertise and investment of time and money. As the tools will form the basis from which estimates are generated for international reporting they need to employ professional software development principles including internal checking, unit testing and version control.

For this reason, countries may opt to use existing tools rather than develop their own. Beyond technical and scientific considerations, there are also practical aspects to choosing an existing tool that must be considered. Changing frameworks can be a costly and time consuming task, so choosing the right one is a key design decision. Some aspects to consider in making this decision include:

▸ **Long-term sustainability of the tool:** MRV needs operate into the foreseeable future and therefore an integration tool should have a good chance of ongoing maintenance and development.

▸ **Support for implementation:** Users will require at least some support to implement integration tools. Although user manuals, tutorials and training workshops are helpful, by themselves they are unlikely to provide all of the information and advice required. It is useful for tools to have a program of support that can be easily accessed on an as-needed basis and an active user community.

▸ **Flexibility and scalability:** Decisions on what ground measurements and remote sensing data to collect and how to analyse them will be driven by the choice of integration framework and the emissions estimation methods to be used. The tool should not only meet short-term goals but be able to support planned future improvements. This could include tools that can support emissions factors but also allow for progression to Tier 3 methods.

There are three options for those wishing to use an integration tool.

1. Use an existing tool

Existing tools cover the full range of Tiers and Approaches and will fit most country circumstances. Each tool has advantages and disadvantages that need to be carefully assessed prior to making any choice (Figure 8: Decision tree for choosing an existing integration tool). These existing integration tools are largely generic calculators that allow use of country specific data. It is possible to use more than one

of these tools for different parts of land use emissions estimation, especially in the context of full land sector inventory for UNFCCC reporting.

2. Adapt an existing tool

There are many models and systems that could be adapted for emissions estimation. Adaptation of an existing tool must be in line with IPCC and UNFCCC requirements, similar to developing a new tool. The costs of adapting an existing tool need to be carefully considered, both in adaptation and maintenance. It will be important to be able to access either the code base or the developers who are responsible for the tool. If only one model is required (e.g., a soils model, DOM model etc.) it may be more suitable to use just the model in an existing integration tool.

3. Develop a new tool

Although developing a new integration tool is possible, the costs need to be carefully considered, both in development and ongoing maintenance. Simple, excel-based tools are likely to be limiting, and unlikely to provide any benefit over existing tools. Specific coded tools are expensive to develop and require specific expertise to maintain. If a new tool is needed then it needs to be developed in line with IPCC and UNFCCC requirements.

It is possible to use a combination of these three approaches, in particular in early phases. For example, Indonesia's INCAS integration framework uses a combination of existing tools for most components, but has developed some simple spreadsheet systems to cover peat emissions. However, it is planned to bring these together in the future in a single tool as part of continuous improvement.

Figure 8: Decision tree for choosing an existing integration tool

Note: a. The IPCC tool currently operates at Tier 1 but is currently being enhanced to allow for Tier 2.
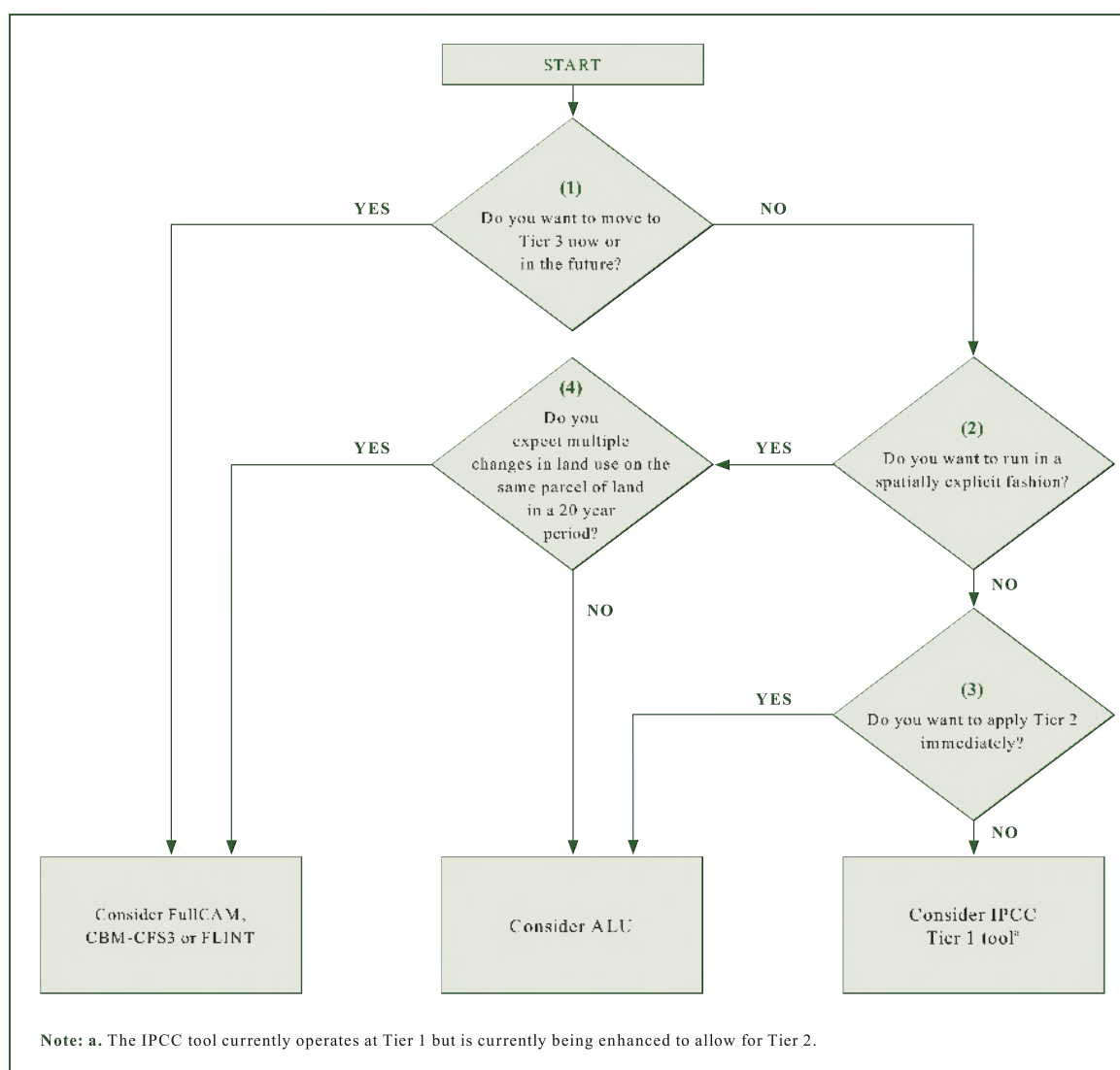
Considerations at the decision points in the tree are as follows:

Decision Point 1: Do you want to move to Tier 3 now or in the future?

> The stepwise approach is consistent with countries which move from lower to higher tiers as data and methods become available. Even if initially reporting at lower Tiers, if there is a desire to move to Tier 3 in the future it is advantageous to do this in the same framework. Moving between frameworks can be costly and time-consuming.

Decision Point 2: Do you want to run in a spatially explicit fashion?

> One motivation for using remote sensing is to allow the tracking of units of land through time (IPCC Approach 3, spatially explicit). To do this requires tools that can use spatio-temporal data that combines time-series in a consistent way.

Decision Point 3: Do you want to move to Tier 2 immediately?

> ALU supports Tier 1 and 2. The IPCC tool supports Tier 1 with plans to develop a IPCC tool that supports Tier 2.

Decision Point 4: Do you expect multiple land use changes on the same parcel of land in a conversion period?

Remote sensing may reveal many areas that have had multiple changes in land use over short periods. Estimating emission on lands where there have been multiple changes in land use unit is challenging when using Tier 1 or 2 methods especially where lagged effects are important, e.g. in the case of soil emissions.

3.3   Guiding principles – Methods and approaches

▸ It is possible to specify systematically, REDD+ activity by REDD+ activity, methods to estimate emissions and removals in a way that links COP decisions and IPCC guidance.

▸ Integration frameworks can help organize data and estimation methods at any level of methodological complexity and facilitate the systematic progression from simpler to more complex methods.

Chapter 4   Remote sensing and ground-based observations

This chapter focusses on the main types and sources of remotely-sensed and ground-based data used operationally for the estimation of emissions and removals associated with REDD+ activities. It includes advice on the use of pre-processed global data sets, particularly the UMD data provided via the Global Forest Watch. It describes the role of NFIs as a source of emissions and removals factors as well as for direct REDD+ estimation. Possibilities are identified for using intensive monitoring sites for model calibration, and the use of auxiliary information for data interpretation and augmentation is described. The chapter recognizes the roles of data in mapping and in providing reference data to correct for estimated bias and estimate precision, as set out in Chapter 5.

4.1   Remote sensing observations

The MGD anticipates that medium- and high- spatial resolution optical and radar data will be the main types of remotely sensed data used in the estimation of REDD+ activities. Currently there is most experience with using medium resolution optical data. This is because:

▶ there is experience in the use of data of this type by countries in making national emissions estimates from deforestation and from other KP LULUCF activities

▶ Landsat provides an historical archive of data of this type back to the early1970s and, given the successful operations of Landsat 8 as well as Sentinel 2A, there is the prospect of continuing availability of data for the foreseeable future

▶ Landsat data are acquired globally and are freely available in pre-processed form (which is also planned for Sentinel 2A), and new techniques in data mining or compositing can do much to mitigate problems of interference by cloud cover. Visual interpretation can also help increase accuracy where there is poor temporal coverage due to cloud.

The CEOS Space Data Coordination Group has worked for GFOI with the world's largest providers of Earth observation data to ensure that all countries can have access to the satellite data required for national forest monitoring and annual reporting of greenhouse gas emissions. The CEOS website has up-to-date information on optical and radar data including spatial and temporal resolution and availability and identifies core data sets which are freely available via the SDCG. The main data types are described below.

4.1.1   Coarse resolution optical data

Coarse resolution refers to a pixel size of greater than about 250m which is generally regarded as too large to be used for generating REDD+ activity data. Changes in spectral indices derived from coarse resolution data e.g. MODIS VIIRS, and CBERS-2 (and eventually Sentinel 3) may be useful in detecting areas where changes are occurring in forests, and this can be used for stratification or to guide sampling. High temporal resolution available from MODIS can help compensate for the coarse spatial resolution by smoothing the time series. High frequency, coarse resolution data can be used to derive a near-real time forest change indicators map, subject to cloud cover limitations, useful for early warning and detection of forest clearing and degradation.

4.1.2   Medium resolution optical data

Medium resolution lies in the range 10 to 80 metres. The most common imagery which may be used for monitoring REDD+ activities is 30 metre resolution, from the Landsat series of satellites (GOFC-GOLD Sourcebook, 2015). Advantages associated with Landsat data include (a) a long history of use, (b) global acquisition, pre-processing and archiving of data, (c) free access to data in the US archive. Landsat will often be the only dataset available for estimating historical activity data. There is an ongoing effort to combine all collections of Landsat data into a single global archive, all processed to the same standards and distributed through the USGS (Wulder et al., 2015). Figure 9: Landsat images collected and expected to be in the Landsat Global Archive by 2017 shows the anticipated state of the archive when the Landsat Global Archive Consolidation (LGAC) process is complete, which should be in 2017.

Figure 9: Landsat images collected and expected to be in the Landsat Global Archive by 2017
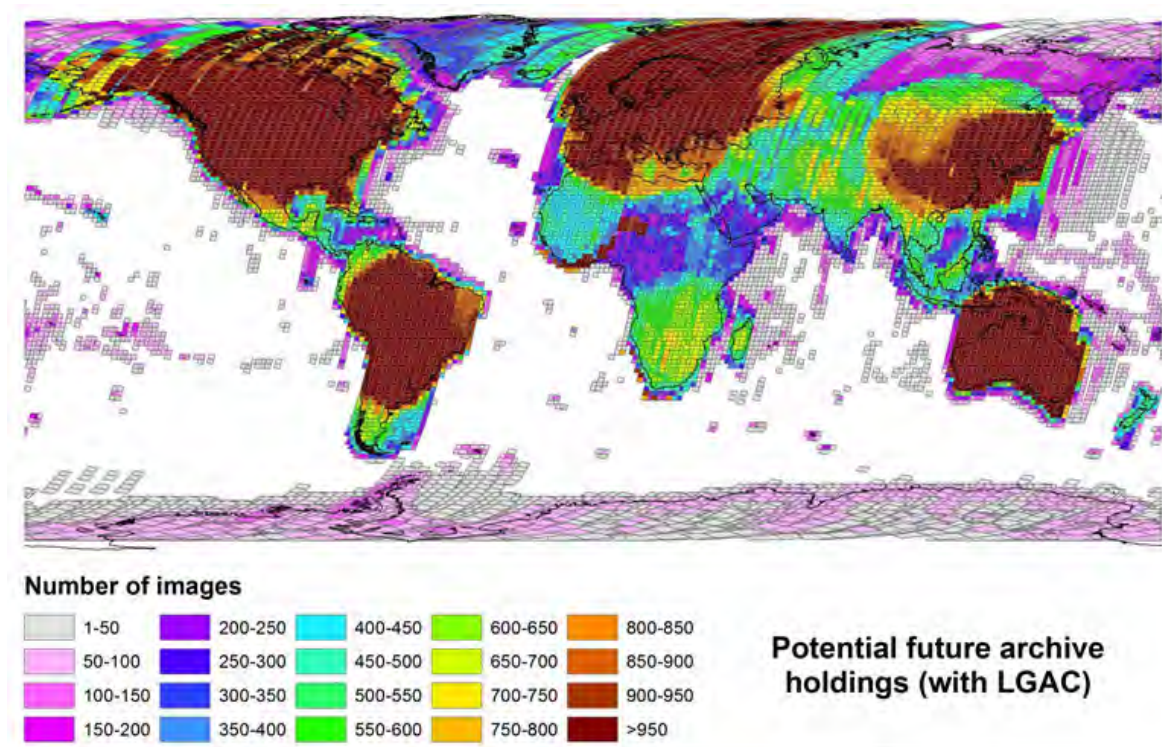
Information is also available from the GFOI on the status of the Landsat archive for individual countries, like the example shown in Figure 10: Distribution of Landsat scenes with less than 20% cloud cover archived for Bolivia for Bolivia. The number of images in the archive increased significantly following the launch of Landsat 7 in 1999. Similarly, the launch of Landsat 8 has increased in the number of images being collected and archived.

The Landsat data series goes back to the 1970s[114] and the successful launch of the Landsat 8 in February 2013 continues the time series for the foreseeable future. Construction of Landsat 9 has begun with an anticipated launch in 2021. The availability of an historical archive is particularly important for establishing reference levels. Similarly, consistent observations over time remains the key to automated methods to detect deforestation and forest degradation.

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[114] Consistent analysis ready Thematic Mapper (TM) images are available from the historic archive dating back to 1984, corresponding to the launch of Landsat 4.

The use of optical sensors is a limitation in areas with persistent cloud cover, but the frequency of data collection has increased in recent years, which helps minimize this issue (see Box 14: Removing clouds and cloud shadows in optical satellite imagery used for mapping activity data) and the accessibility and global coverage associated with Landsat generally make it the first data source to consider for a NFMS. For many purposes Landsat will serve to fulfil national remote sensing data requirements associated with REDD+ activity data collection. For example, the Landsat archive opens the possibility of conducting historical time series analysis within the suggested temporal ranges suggested for developing FREL/FRLs (10-15 years - Chapter 2, Section 2.3.3) and the confidence that this data source will be available for future monitoring requirements.

The CBERS-4 and Sentinel 2 satellites will increase availability of medium resolution data, including by making 10 m resolution data freely available and facilitating applications which have hitherto been regarded as only possible at high resolution.

Countries having national operational programs for forest cover monitoring using Landsat or Landsat-like data include Australia (Furby et al., 2008), Brazil (DMC and CBERS; Souza, 2006), India (IRS; Pandey, 2008) and the United States (Fry et al., 2009).

Figure 10: Distribution of Landsat scenes with less than 20% cloud cover archived for Bolivia

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
L8																								421	553	598
L7										289	404	361	424	341	433	475	454	411	496	447	469	447	499	460	409	404
L5	330	394	288	382	308	362	423	334	440	463	386	419	78	299	498	484	477	473	447	458	419	332				
L4		3	20	1																						
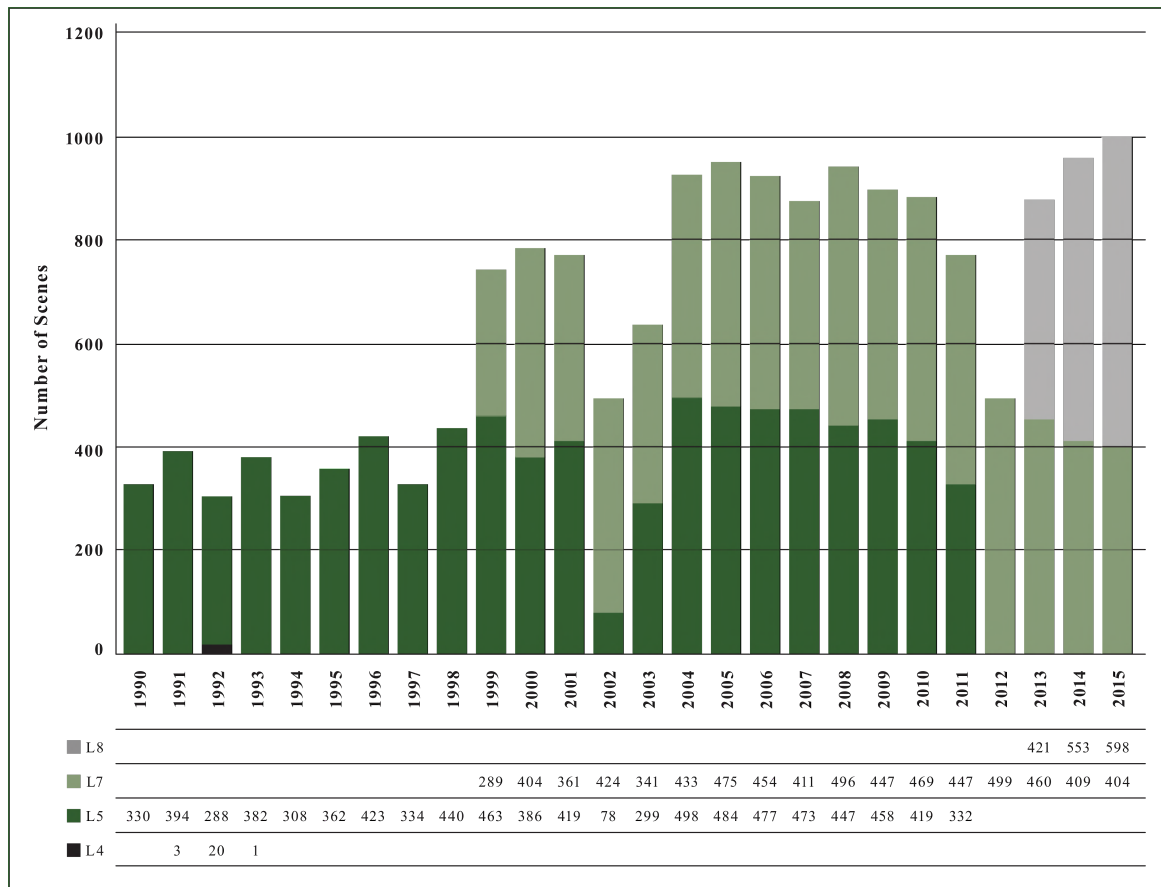
Box 14: Removing clouds and cloud shadows in optical satellite imagery used for mapping activity data

As explained in Box 23: Time series analysis of earth observations for monitoring of activity data, with the opening of the Landsat archive in 2008 (Woodcock et al., 2008) time series of Landsat data can be obtained for almost any location on Earth. Clouds can cause difficulty with optical sensors though techniques exist to address this: when classifying a single image or an image pair, it is straightforward to identify and classify any obvious clouds and cloud shadows (contaminations) present in the image. These pixels can then be removed from the analysis or replaced by pixels from cloud free images from the closest available point in time. .

When analysing a time series of observations for land surface activities using all available images, clouds and cloud shadows need to be accurately identified as anomalies in the time series which the classification algorithm could wrongly attribute to surface activities. Fortunately, use of a time series itself makes it easier to do this. For example, when using continuous change detection and classification (CCDC) for mapping activity data (Arevalo, 2016; Olofsson et al., 2016), the analyst first applies an algorithm that looks for clouds and cloud shadows screening each image individually but without use of previous or subsequent observations (Zhu & Woodcock, 2012b). A second algorithm, looking now at each pixel as part of the time series, then checks whether the omitted pixels were in fact anomalies or real changes at the surface time (Zhu & Woodcock, 2014a). The single image cloud screening algorithm referenced here, Fmask, is currently being implemented by the USGS to screen all Landsat images in the US archive, such that each image will be delivered with a Fmask-based cloud/cloud shadow mask. Fmask is not the only published algorithms that screen for clouds in Landsat images – many similar algorithms have been published in the last decade (Huang et al., 2010; Irish et al., 2006; Masek et al., 2006; Roy et al., 2010; Scaramuzza et al., 2012). These semi automated processes can still miss cloud and haze and should always be accompanied by manual checks and, where necessary, manual cloud, shadow and haze removal. As also mentioned in Box 23: Time series analysis of earth observations for monitoring of activity data, an alternative use of a time series is to create composites by selecting certain observations in a time series according to some criteria. For example, if the median of the surface reflectance of annual time series of Landsat observations is computed, annual images are created that are free of cloud and cloud shadow provided that clouds are not present for most of the year. More advanced criteria can be developed that take phenology, spectral ratios, advanced statistics and/or results from a cloud screening algorithm into account (Griffiths et al., 2014; Hansen et al., 2013; Kennedy et al., 2010).

The discussion here focuses on Landsat because currently it is the only mission that provides free data in combination with a long enough record to allow for time series analysis. It also has a thermal band that helps in the identification of clouds. In the future, we will be able to construct time series of other data, including Sentinel-2 data, which lacks a thermal band but like Landsat-8 has a cirrus band that has been found to be helpful in the identification of clouds (Zhu et al., 2015).

4.1.3 High resolution optical data

High resolution (finer than 10 metres) data can improve detection of changes associated with degradation, and allow REDD+ activity data generally to be monitored more accurately and with greater differentiation than medium resolution data. There are some examples of countries making use of high resolution data for wall-to-wall mapping for REDD+ including Mexico and Guyana (Box 15: Use of

high resolution data in the mapping context– Guyana), but acquisition and processing costs are higher than with medium resolution data. Also high resolution data may not be available for entire countries for a sufficient number of time periods to allow direct estimation of REDD+ activity data from wall-to-wall coverage.

Consequently, so far high resolution optical data have been used mainly in sample-based verification or accuracy assessment, for sampling transects or local areas or regions of interest, and for assessment of *hot spots* where changes are occurring or are more likely to occur. High resolution data may also be valuable for providing training data for change detection algorithms and can be used to produce emission and removal estimates and factors – e.g. the application of LIDAR (see below) to estimating depth of peat combusted by fire in Indonesia, and hence emissions of carbon dioxide and non-carbon dioxide greenhouse gases (Ballhorn et al., 2009). The use of high resolution data continues to be the subject of research.

Box 15: Use of high resolution data in the mapping context– Guyana

Guyana has developed a MRV process which provides the basis for performance measurement which has drawn on a capacity building Roadmap spanning the period 2010 to 2013, and includes the forest carbon monitoring system and forest cover assessment. The work has been supported under the terms of the Joint Concept Note which Guyana and Norway signed in 2009[a]. Guyana began developing its historical (1990) land cover change baselines from freely-available 30 m Landsat imagery. A review by the Guyana Forestry Commission (GFC)[b] after the first year of operation (2011), lead to opting for high resolution RapidEye imagery to cover the most active change areas. Today the MRV processes conform to IPCC approach 3. All post 1990 land cover changes (including non-anthropogenic changes) greater than 1 ha as detected are mapped and stored as a GIS. From 2011 onwards the MRV process included the mapping and monitoring of forest degradation (or canopy disturbance) surrounding deforestation events at a national-scale. Overall change areas are estimated using a combination of mapped and reference data and the spatially explicit data is also used for assessing the effect of drivers. An independent accuracy assessment conducted in 2013 quantified the accuracy of the deforestation and forest degradation mapping at 99% and 80%[c] respectively.

The process designed and adopted by GFC has developed over time, and integrates good practice linked to operational research focused on developing methods appropriate for the forest degradation drivers. The MRV design recognises the problem of persistent cloud cover, the spatial scale and the intensity of the land cover change. To address these, frequent coverage of high resolution imagery is used. As with many countries, considerable expertise in Guyana resides in the use of GIS rather than in remote sensing technologies. Given these challenges, a GIS-based MRV process has the advantage of being adaptable, user friendly and flexible enough to incorporate a range of different data types required to meet IPCC requirements.

The change detection processing chain is semi-automated with each satellite image assimilated and batch processed. The processing includes conversion of images to reflectance, atmospheric normalisation, detection and delineation of land cover change using vegetation indices, and conversion of these changes to a GIS format. The quality of the change delineation is systematically assessed and edited by trained analysts who also attribute a change driver to each polygon. The attribution options are illustrated in mapping documentation with the attribution process controlled by the use of a customised GIS toolbar. The toolbar stores all relevant attributes and assists the operator to ensure appropriate land cover change and driver combinations are selected. Image 1.1 provides an overview of the mapping flow, from satellite images (A) to creation of a pre-processed change layer (B) to the generation of a multi-temporal forest change products (C).

Normalised Imagery (A)   Change Detection (B)   Attributed Change (C)
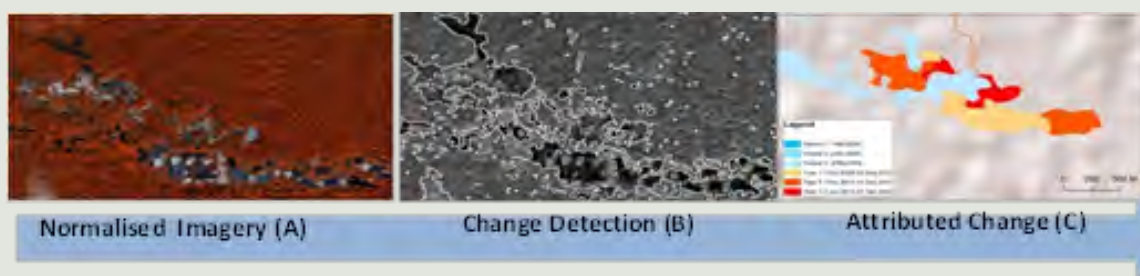
Forest degradation mapping is undertaken in conjunction with deforestation mapping. The scale (<1 ha) and intensity of degradation is known to vary by driver (i.e. mining prospecting, timber extraction, or shifting cultivation). Degraded forest is identified from temporal persistence of canopy disturbance. Further monitoring is used to determine if the changes in the canopy can be considered forest degradation, linked to a significant percentage reduction in carbon stocks in the areas affected, or just temporary disturbances that recover in a short time period. To detect forest degradation on satellite imagery the disturbance must occur at a scale that causes a visible change in the canopy. Using the method adopted, the pixel resolution and temporal frequency of sensors such as Landsat and DMC are insufficient to detect forest degradation related to canopy disturbance.

Notes: a. The JCN sets out a series of interim measures that are intended to be used whilst the full MRV functionality is being developed. b. The implementing Agency with technical assistance provided by Indufor Asia Pacific

4.1.4 L-band Synthetic aperture radar

The potential ability of imaging radar (also referred to as Synthetic Aperture Radar, SAR) to provide activity data has been demonstrated at the subnational (Mitchell et al., 2012) and regional (project) level and could be useful, particularly in areas of persistent cloud cover, as well as in combination with optical data. In a volume (such as a forest canopy), the radar signal tends to interact more strongly with scatterers of comparable size or larger than the wavelength; shorter wavelengths, such as X- and C-band, respond more to the leaves and twigs, while L-band will hardly see the leaves but will see larger branches.

Current and near-future SAR systems have multi-polarisation capacities which, like the different spectral bands of optical data, provide additional information. SAR systems can provide information that is not visible in optical data (and vice versa) and the two data sources are therefore to be regarded as complementary, not competing.

An additional advantage of the cloud independence of SAR is that large regions can be acquired within relatively short time windows (few weeks – few months), reducing the need to fill in data gaps with data from different years or different seasons. Consistent archives of global or regional wall-to-wall data exist for some historical SAR missions for certain time periods (JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2), and through the CEOS Data Strategy for GFOI, such systematic acquisition strategies are becoming standard for several of the near-future core and non-core SAR missions (Sentinel-1, SAOCOM-1, ALOS-2, RCM). L-band SAR.

With a wavelength of about 23.5 cm, L-band SAR penetrates through the forest canopy and generally provides clear distinction between vegetated and non-vegetated areas. It is commonly used for mapping of forest/non-forest, and with time series of data, for detection of forest cover changes. At least two polarisations are preferred, because the cross-polarisation channel is particularly sensitive to forest structural parameters, such as twigs, branches and stems, and thus indirectly to forest types and age classes. L-band SAR is also linked to above-ground biomass up to a level of about 100 tonnes per hectare, although this is an area of research (Lucas et al., 2010; GEO, 2011) and accuracy levels are currently insufficient for use for GHGI estimates.

Semi-annual wall-to-wall observations over the global forest cover were undertaken by ALOS L-band SAR (PALSAR) between 2007 and 2011 and by ALOS-2 PALSAR-2 since 2014. 25m resolution PALSAR and PALSAR-2 global mosaic data are open to the public and can be accessed from JAXA. The

SAOCOM-1 L-band SAR constellation (launch 2017/2018) will feature a similar systematic acquisition strategy that will provide cloud-free coverage over the pan-tropical regions several times per year.

High temporal frequency, coarse (100 m) resolution L-band SAR data acquired in so-called ScanSAR mode have demonstrated potential for early warning of forest clearings (e.g., INDICAR system of IBAMA, Brazil (de Mesquita, 2011). L-band SAR is considered to have operational capacity to map forest cover and changes (GEO, 2011; Walker et al., 2010), and to be pre-operational for deriving land cover (GEO, 2011), activity data (Mitchell et al., 2012; Lucas et al., 2010), forest sub-stratification (GEO, 2011; Hoekman, 2012) products as input to emissions estimation. Combined use of different sensor types (e.g. L-band SAR and optical, L- and C-band SAR) can improve discrimination of forest and land cover types (Holecz et al., 2010).

4.1.5 C-band and X-band SAR

SAR systems operating at shorter wavelengths (C-band: 5.6 cm; X-band: 3.1 cm) typically reflect from the surface and top layer of the forest (leaves and twigs) and thus provide information about canopy structure. While the contrast between forest and low vegetation generally is less distinct compared with longer wavelength SAR, the use of two polarisations improves discrimination. X-band SAR data can be acquired at a spatial resolution better than 5 metres, which allows more detailed characterisation of forest canopy structure and although still regarded as research, has potential to provide information about forest degradation (e.g., selective logging (Baldauf, 2013)).

Frequent time series of C-band SAR data has demonstrated capacity for detection of changes in forest cover, and has potential for use for early warning of forest clearing. For forest-related C-band applications, data collected at dual-polarisation (including one cross-polarisation channel) is a critical requirement. To avoid confusion with changes occurring in other land cover classes, change detection can be applied relative to a pre-determined forest area derived e.g. from optical or L-band SAR data.

Sentinel-1A and -1B (successfully launched in 2014 and 2016) are C-band core missions. They will provide intra-annual observations of all global land areas, with potential higher frequency observations over selected countries or regions. Data from the Sentinel 1 missions are being distributed with a free and open data policy, making it an attractive option for monitoring forest activities in the tropics. Data can be accessed through the Copernicus data hub as well as the Alaska SAR Facility.

Amongst non-core missions, a full global coverage of X-band SAR data have been collected by the TanDEM-X satellite constellation.

4.1.6 LIDAR

LIDAR sensors emit pulses in near-infrared wavelengths that interact with different strata and from which quantitative information on forest structure (e.g. tree height, canopy volume) and biomass can be estimated. LIDAR-assisted biomass estimation using wall-to-wall coverage of satellite data is a research topic of interest for future forest monitoring systems. Although an historic archive of satellite LIDAR is available[115], there are currently no operational LIDAR satellites. The NASA ICESAT-2 mission for a space-borne LIDAR is planned to be launched in 2017, and the GEDI mission is scheduled for launch before 2020. Subject to the demonstration of suitable techniques, space-borne LIDAR could be used for estimation and cross-checking with other methods. Airborne LIDAR, following calibration using

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[115] Refer to the ICESAT-GLAS data archive.

appropriate ground estimates of biomass, can be used to produce reliable high resolution biomass maps (Stephens et al., 2011[116], Goslee et al., 2015) and can be cost effective in some national circumstances, e.g. where terrain makes access difficult. Box 16: Use of LIDAR by Nepal and Box 17: Use of LiDAR in Tanzania summarize practical experiences with LIDAR, in Nepal and Tanzania respectively.

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[116] When building the national reporting system for New Zealand concluded that airborne LiDAR with appropriate plots in a bound-sample found that a "reduction in standard error achievable using LiDAR is expected to be approximately 50% for total carbon and 55% for AGB carbon.

Box 16: Use of LIDAR by Nepal

The Department of Forest Resource and Survey (DFRS) of Nepal[a] conducted a comparison between the use of airborne LIDAR, high resolution RapidEye satellite data versus conventional ground-based techniques for estimating above-ground biomass.

The first approach applied a model-based LIDAR Assisted Multisource Program (LAMP), integration 5% LIDAR sampling, wall to wall Rapid Eye satellite images, and in situ measurements from 738 field sample plots of 12.62 m radius (in LIDAR sample areas) over the 23300 km^2 Terai Arc Landscape (TAL) area of Nepal during March to May 2011 to estimate AGB.

In the second approach the field based multisource forest resource assessment (FRA) began in January 2011. The field based approach utilised a design-based forest monitoring method incorporating space technology, auxiliary data, and intensive field inventory. A total of 676 concentric circular plots (CCP) of radii 20m, 15m, 8m and 4m were designated systematically in TAL area to measure tree characteristics, including the attributes required for calculating AGB.

Both field plot-based FRA method and the LIDAR assisted LAMP approach were compared with respect to their accuracy in estimating mean AGB for the region at different spatial scales. The mean error of the FRA estimated at 1 ha was 6243.95 tons/ha which is impossibly high, but this decreases slowly with increasing estimation area and goes down to 10.6 tons/ha when the estimation area reaches 350,000 ha. The mean error for the LAMP approach was 13.21 tons/ha for 100 ha of forest which demonstrates acceptable accuracy to estimate biomass stock in management level forest regime such as community managed forests of the TAL area where the average size of community forests is 150 ha. Error calculation for the two approaches shows the importance of considering national circumstances (in this case accessibility and typical size of community forests) in deriving national approaches (Kandel et al., 2013).

Whilst the LAMP approach achieved lower uncertainty, the FRA approach had lower baseline data collection costs. However, LAMP was found to be the more cost effective approach for repeated forest monitoring required for MRV.

The results show that the biggest difference between the two approaches is spatial resolution. LAMP has higher accuracy reliability over smaller spatial extent compared to conventional multisource forest inventory.

This study reinforced that choice of inventory method should be made depending on the reason for the inventory (e.g. MRV vs. forest industry management) and the cost of measuring forest variables. Through the FRA method, information about a vast number of target variables can be collected, ranging from tree-level characteristics to biodiversity and soil. The LAMP method covers significantly fewer forest variables and cannot replace a multisource inventory. However, LAMP produces biomass and carbon stock estimates at high spatial resolution. For estimation of forest biomass/ carbon stock and establishing an MRV baseline, LIDAR-assisted inventory was preferred because subsequent monitoring cost is low.

Notes: a. in collaboration with in collaboration with WWF-Nepal and Arbonaut

Box 17: Use of LiDAR in Tanzania

Miombo woodlands are the dominant forest type in eastern Africa and occupy around 9% of the African land surface south of Sahara. They account for approximately 90% of the land area of Tanzania. Miombo woodlands are fragmented with mainly open forests, and in many areas they are subject to severe degradation and conversion to agricultural land.

Tanzania has recently established an NFI consisting of over 30,000 ground plots across all land use categories distributed according to a stratified and systematic sampling scheme on a 5-km × 5-km grid. To explore the possibilities of enhancing the precision of AGB and hence carbon stock estimates, and stock change estimates, airborne scanning LiDAR was used as a sampling device in combination with the existing NFI. Previous studies had shown that it can be efficient to sample with LiDAR as opposed to collecting wall-to-wall data due to reduced costs and only marginal reduction of the precision of estimates.

For trial purposes a 16,000 km^2 miombo woodland area in Liwale district of SE Tanzania, was subject to LiDAR strip sampling. Thirty-two parallel LiDAR strips were distributed in the E-W direction with a distance between strips of 5 km. Each of the LiDAR strips was wider than 1 km and covered >25% of the total area. LiDAR data were collected in 2012 and repeat LiDAR measurements were acquired along the same strips in 2014. Coincident ground observations were obtained on 531 NFI plots along the strips in 2012 as well as in 2014.

Numerous analytical estimators for biomass and variance of biomass estimates for different types of LiDAR-based sampling applications have been derived over the past 10 years. Some assume probability sampling of LiDAR strips and field data, while others assume probabilistic sampling of LiDAR data and permit opportunistic collection of ground data in areas that are accessible. Different types of estimators were used to estimate AGB and change in AGB over a period of two years.

It was shown that LiDAR could greatly improve the precision of AGB estimates. The LiDAR-assisted estimated mean AGB across the entire area was 59.7 Mg ha-1 with a standard error (precision) of 1.73 Mg ha-1 for the LiDAR-assisted estimate and 4.79 Mg ha-1 when using only the field data. It was shown that by using LiDAR in combination with the field survey, the overall costs could be reduced while maintaining precision by reducing the field sampling effort. However, given that the NFI is a continuous inventory system, reducing field efforts may not be an option. Also, an NFI provides information on many other aspects of forests than just biomass which cannot be acquired by remote sensing.

Change estimates over the 2-yr period showed a loss of biomass of 0.26 Mg ha-1 (0.22% per year). The standard error was 0.81 Mg ha-1. An approximate 95% confidence interval would range from -1.36 to 1.88 Mg ha-1, i.e., spanning an interval from increase in stock to a decrease in stock. As opposed to the stock estimates, the precision of the change estimates did not improve by using LiDAR in addition to the field plots. Consequently, the use of LiDAR for change estimation was not cost-efficient. More information can be found in *Forest monitoring with airborne laser scanning in Tanzania*, Erik Næsset (editor), INA fagrapport 31, ISSN, Norwegian University of Life Sciences 2015 (ISSN 1891-2281).

4.1.7 Global forest cover change datasets

Global maps of land cover, including tree cover, are readily available[117]. Work led by the University of Maryland (UMD) (Hansen et al., 2013)[118], provides tree cover, and cumulative tree cover gains and annual losses. The UMD maps are produced on a consistent basis and are updated annually. While there are plans to produce annual tree cover maps, currently the maps do not track multiple changes in tree cover through time, meaning that regrowth following loss is not tracked. This limitation needs to be considered when deciding to use the data to produce emissions and removals estimates.

The maps have 30m x 30m spatial resolution and are based on Landsat data. Depending on national circumstances they may provide countries with change maps if suitable maps do not already exist for their territories. This section provides advice on the use that can be made of this type of data for REDD+, mainly for activity data estimation, and discusses the issues that can arise in doing so.

Accuracy of global products varies regionally due to factors including differential sensitivity of detection at biome and ecoregional scales; change dynamics (e.g. at smallholder to industrial scale), and data richness (affected e.g. by cloud cover; better quality observations, and more observations will improve accuracy). In general, use of global maps will produce activity data estimates with lower accuracy and precision than are attainable by national mapping of comparable quality, because the latter can be tuned to national forest definitions and make use of knowledge and auxiliary data available at the national level. However as set out in Chapter 5, Section 5.1.5, correcting for estimated bias at a given level of precision depends on the combination of mapping (whether global or national) and reference data. Because of this, when correcting for estimated bias, lower accuracy associated with global datasets can be compensated by using more ground or other reference data, and global datasets may enable progress to be made until national mapping capacity is established. Global datasets and national mapping capacity can therefore be seen as complementary. There are country examples demonstrating the joint use of global data and national expertise (Box 18: Use of global data sets – Ethiopia; Appendix D).

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[117] This section is based largely on Use of global tree cover and change datasets in REDD+ Measuring, Reporting and Verifying (MRV) (GFOI MGD Module 2, published 28 March 2015) plus material from the joint GFOI-GOFC-GOLD Expert workshop on using global datasets for national REDD+ measuring and monitoring, Wageningen University, November 2015.

[118] The UMD data are available via the World Resources Institute Global Forest Watch web-site. Other data sets are the ESA Land Cover Climate Change Initiative at 300m:,the Global Land Cover dataset at 30m from China for 2000 and 2010, and Do-Hyung Kim et al, (2014). *Global, Landsat-based forest-cover change from 1990 to 2000*, Remote Sensing and the Environment 155: 178-193. For a review of global data sets see Tsendbazar, N.E., et al. (2014) *Assessing global land cover reference datasets for different user communities*. ISPRS J. Photogram. Remote Sensing.

Whether using a national or global map, the process is the same, namely:

▸ decide the precision required. This is likely to depend on the policy context including expectation of results-based payments (Chapter 2, Section 2.3). Discussion between technical experts and policy colleagues on what can be achieved cost effectively may be needed.

▸ obtain an initial, exploratory reference data set[119].

▸ based on the results of using the exploratory reference data and the map to indicate the precision obtainable as a function of sample size, gather additional reference data to correct for estimated bias and obtain the precision required.

Relative efficiency is a measure of the improvement in precision obtainable by using map data and reference data in combination. Box 19: Relative efficiency shows how relative efficiency is defined and draws some overall conclusions about typical relative efficiencies obtainable from national and global mapping

Consideration of relative efficiency can help decide upon cost effectiveness (e.g. the cost of collecting more reference observations versus establishing a national mapping capability, and costs of establishing the relationship between global maps and national forest definitions). National assessment of the relative advantages of global and national maps to generate national level estimates of forest area and change are also related to:

▸ preferences for national ownership of the process, to respond to technical developments

▸ the need for information on the drivers of forest and land cover change, particularly when this information is required for results-based payments

▸ whether national mapping capacity already exists – countries with mapping capacity are likely to want to use it

▸ national needs for a land cover map (e.g. related to forest definition and land cover classifications, for integration with domestic planning).

The relationship between global data and the national forest definition is important and in comparing national estimates and global products the user should ensure that both products cover the same geographic extent and time period[120] and that the forest areas and area changes derived from the global data correspond as nearly as possible to the national definition. Common inconsistencies between global data and national forest definitions are related to the minimum canopy cover thresholds[121], detailed consideration of land use (e.g. the status of shifting cultivation, oil palm or other plantations), the minimum size of forested areas, and the minimum tree height required by the definition. The global maps available from UMD indicate three main characteristics: (i) percentage crown cover for vegetation over

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[119] Reference data are high quality ground or independent remotely sensed data that can be used with map data or independently to correct for estimated bias and estimate confidence intervals. Use of reference data is described in Chapter 5.

[120] Any global or national map starts at a certain temporal reference point. For example, the UMD map quantifies change annually from the year 2000. In a national context countries may have different starting temporal baseline

[121] Canopy cover thresholds would not necessarily fit with the national definition when the minimum forest area tends to be very different to the Landsat pixel size. In addition, there may also be calibration issues with the global data related to phenology or radiometric quality of the input data.

5 metres in height[122],[123] (ii) tree cover loss (areas where tree cover has been removed entirely) and (iii) tree cover gain (areas where tree cover has been established where previously there was no tree cover).

Rules to map the extent of the minimum percentage crown cover[124] specified in the national forest definition could be implemented automatically in the case of the UMD data, because percentage crown cover is a pixel-level attribute. However some studies indicate given crown cover (say 30%) in the national forest definition may not correspond to 30% as estimated in the global dataset (Sannier, et al., 2016; McRoberts et al., 2016). This would necessitate an adjustment or compensation, using either auxiliary data to establish the relationship, or by treating the adjustment as part of the bias correction via the reference data set. Other criteria to define forest, such as a different height specification, or specific land use requirements, imply the need for supplementary national mapping (with significant associated cost) to correct for areas either erroneously included or excluded by the global maps. To help achieve this, the NFMS could identify areas that would otherwise meet the forest definition, but are under predominantly agricultural or urban land use, and identify ecosystems where trees do not meet the height definition.

Accommodating the minimum area, tree height, width, and canopy cover requirements of a forest definition is non-trivial with pixel-based maps, whether global or nationally produced. Although object-based and GIS methods may be useful, pixel elimination and aggregation rules[125] must be applied for consistency with the applied definition, which may degrade the spatial resolution of the map and involve complicated averaging methods to estimate percent canopy cover for the aggregated units. In practice, straight-forward and easily implemented techniques to do this are not readily available[126].

Global map products indicating areas where tree cover has been removed entirely can be used to help map forest/non-forest land cover change[127]. However, areas where complete overstorey removal

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[122] In the case of the UMD data the mapping is tuned to detect tree cover about 5 m height. Tree height measurement by remote sensing requires interpretation of stereoscopic images or a returned signal from SAR or LIDAR which are not commonly available.

[123] Tree cover gain is defined as detected increase in crown cover over the entire period 2000 to 2012. This information could be used in mapping tree regrowth, replanting and establishment areas over the entire period. Because increase in crown cover over time is harder to detect than abrupt loss, the forest gain product is likely only to be of value when used in conjunction with some form of local field data or a sampling procedure. Therefore the points made here on the use of reference data and relationship to national mapping capacity apply with even greater relevance than in the case of deforestation estimates.

[124] The relative performance of global and national classification methods may be a function of the crown cover threshold used in the national forest definition.

[125] Rules need to be defined when contiguous pixels below the specified threshold should belong to the surrounding forest area or be considered as non-forest. Introducing the concept of Minimum Mapping Area (MMU) can be useful in this context. Rules also need to be defined when characterizing changes. It can be decided that changes below the minimum forest area are considered as long as they aggregate with forest areas that are greater than the set minimum forest area.

[126] The Australian National Greenhouse Gas Inventory approach to reporting land use, land use change and forestry applies such methods.

[127] At the time of writing the UMD data do not yet provide updated global forest cover maps.

is indicated will not necessarily correspond to deforestation as a process of change in land use in accordance with the national forest definition, because:

- deforestation, consistent with the national forest land definition, entails land use change and occurs when areas previously meeting the forest definition fall below the minimum tree cover, height or area thresholds without prospect of recovery. This is not necessarily the same as complete removal of tree cover.

- tree cover may fall temporarily to zero (or below the minimum threshold specified in the national forest definition) because of harvest or natural disturbance (e.g. fire, wind, disease or landslides), but this does not indicate a change from forest land use if replanting, or natural or assisted regeneration will take place so that forest according to the national definition will be re-established.

Use of global datasets to estimate deforestation therefore needs to take into account factors other than simply using the global analysis of removal of tree cover below the minimum level that is estimated by the global data set classification algorithm. This is likely to require auxiliary information to identify areas subject to harvesting where replanting will take place, and information on the extent of any disturbances, and whether they have been followed by land use change, or not. Time series analysis has the capacity to be extremely helpful. The auxiliary information required should be obtained by interaction with stakeholders via the NFMS or other institutional arrangement responsible for land use. Modifications introduced via auxiliary data need to be treated consistently over time, or significant error may be introduced into mapping and area estimation. UMD provides Landsat image mosaics for the years 2000 and 2015 which could be interpreted by the user to provide a map that includes information on land use change drivers.

Reference observations consistent with the national forest definition can also be used with an unmodified global map. The reference data are used to adjust for estimated bias resulting from map prediction error when using global map products as the basis for estimation, but the amount of reference data needed to achieve given precision is likely to be greater in this case. If the reference data are stratified, e.g. by forest type, accessibility, or biomass quantity[128], strata should be applied consistently over time irrespective of whether national or global map products are being used.

The methods for using reference data, described in Chapter 5, Section 5.1.5, yield area estimates of land classes (e.g. forest, non-forest, forest loss and forest gain) that are adjusted for estimated bias. However these methods are not designed to determine which pixels are misclassified[129]. This means that the act of area (or area change) estimation with reference observations does not improve site-specific mapping accuracy (at the level of individual pixels or minimum mapping units). Consequently if maximum possible site-specific accuracy is needed (e.g. for interacting with stakeholders, identifying drivers of deforestation[130], or associating ground-based with remotely sensed data for development of emission/removal factors) it may be better to develop national mapping using classification methods designed for national circumstances[131]. Achieving a particular accuracy in either case is likely to require an initial trial

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[128] Samples corresponding to the same strata drawn from global biomass maps may help in identifying corresponding biomass carbon densities, or for cross-checking biomass estimates from national sampling.

[129] Misclassification of individual pixels or other sampling units corresponding to the reference sample can be determined, although these will generally be a very small proportion of the study area.

[130] Or other REDD+ activities

[131] See Section 4.1 for discussion of image classification.

followed by additional reference observations sampling or improvements to the classification technique until the desired result is obtained.

The choices are summarized in the decision tree Figure 11: Guidance on the use of global data sets for estimating forest cover and cover change below. Although national mapping should be more accurate and precise, global maps have value as a cross check because differences should be understandable, e.g. in terms of the factors discussed here.

Figure 11: Guidance on the use of global data sets for estimating forest cover and cover change

Note: a. It is assumed that countries will want to develop national capacity. Factors relevant t this decision identified in the text include preferences for national ownership, cost relativities, of national mapping or global datasets plus increased reference sample size and ability to respond to technological developments.
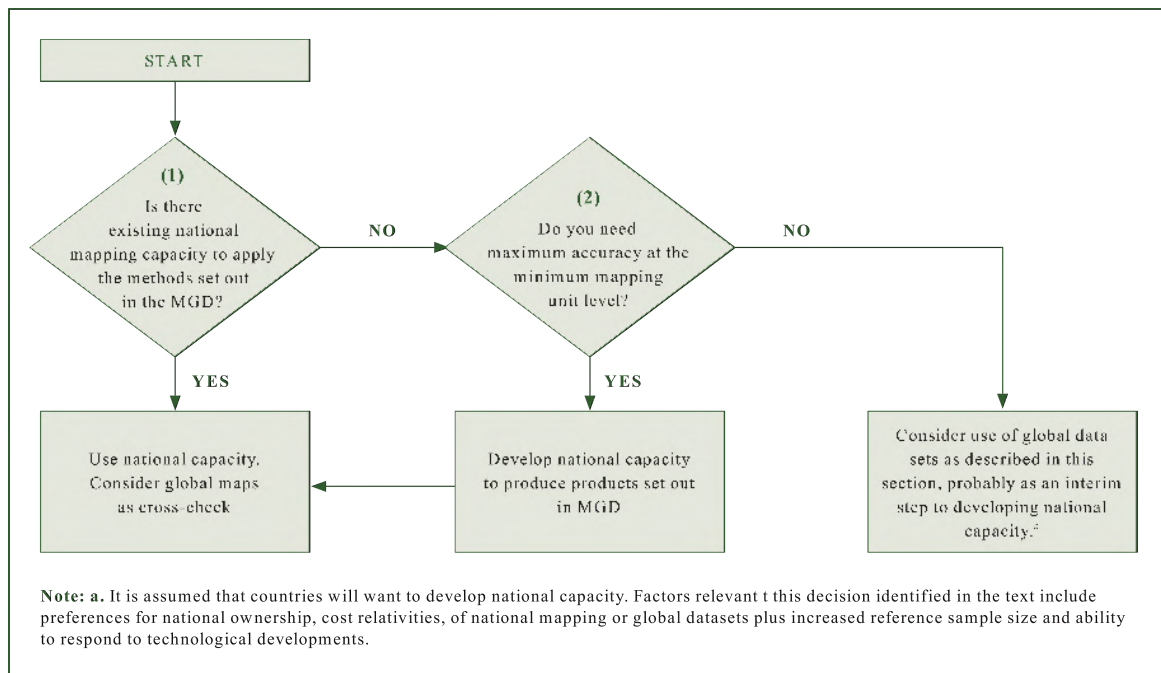
Considerations at the decision points in the tree are as follows:

Decision Point 1: Is there existing national mapping capacity to apply the methods set out in the MGD?

> The methods for generating national activity data from remote sensing are outlined in 4 and 5. All cases assume joint use of mapped and reference data.

Decision Point 2: Do you need maximum accuracy at the minimum mapping unit?

> Maximum accuracy at the minimum mapping unit may be required for interaction with stakeholders, identifying drivers, associating remotely sensed and ground-based data or nesting of sub-national activities.

Box 18: Use of global data sets − Ethiopia

In the context of the "Implementation of a national forest monitoring and MRV function for REDD+ readiness in Ethiopia" project, the Federal Democratic Republic of Ethiopia has initiated a series of activities to: a) develop a forest definition and a classification system; b) generate land cover change maps and statistics; c) collect data from the field or develop allometric models.

To date, several institutions in Ethiopia have carried out preparation of land cover maps including the Ministry of Environment, Forests and Climate Change (MEFCC, 2013), the Ethiopian Mapping Agency (EMA 2003, 2008 and 2013) and the, Central Statistical Agency of Ethiopia (CSA, 2008). However, these products lack the accuracy or time dimension to provide statistics and spatial analysis of forest change over time needed for the establishment of FRL. The Global Forest Watch (GFW) product (Hansen et al., 2013) was used as a first step to indicate where potential losses and gains within forest lands have occurred at the national scale.

In the absence of reliable data sources indicating areas of changes at the national level, a preliminary training dataset was generated automatically from the GFW product. The GFW product was down sampled to 3x3 pixel kernel to reduce the inclusion of potentially false classifications in the training datasets. The resulting product was randomly sampled with 300 points for 3 classes (loss, gain and no change).

The points for losses and gains were carefully assessed by national remote sensing experts to ensure the samples were an accurate representation. Visual assessment using very high resolution imagery available in the Google Earth, Bing Maps, and Here maps repository was performed through the Collect Earth interface. Ethiopian remote sensing experts identified additional training data in order to meet the national definition of forest (i.e. Height: 2 meters; Canopy Cover: 20%; Area: 0.5 hectares), which differs from the definition in the global product (i.e. Height: 5 meters; Canopy Cover: 25%; Area: 0.09 hectares). Classification of the image involved compiling the spectral signature for all the training points, creating a model from this spectral library and applying the model to the entire imagery. Two models for supervised classification were tested, the CART algorithm (Breiman et al., 1984) and the Random Forest algorithm (Breiman, 2001). After the first classification, the training datasets were improved by visually assessing zones of obvious false change, stable classified as change and missed changes and change classified as stable. The training sites were added to the misclassified locations for the correct class. The new sites were entered in the spectral library with appropriate classification. The classification process was iteratively repeated by carefully checking the batch of results.

The processing chain, from classification of the change, iterative improvement of the training data, and export of the results was performed in the Google Earth Engine API, with the script available here[132] .

The accuracy of final change product change was assessed using the methodology described in Olofsson et al., 2014.

Manual cleaning was finally performed (filtering out of zones of change to match the national MMU=0.5 ha ~5 pixels and manual delineation of mis-classified zones) using the 2013 MEF land cover map to filter out loss detected to occur on the forest mask.

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[132] A Google Earth Engine API Trusted Tester account is needed to open this link

The GFW global data set provided Ethiopia with a starting point for identifying areas of change, however the land cover and land use dynamics in Ethiopia are extremely complex and not fully captured by the global product. Therefore, inputs from national experts was critical for a robust classification in respect of possible errors of omission and commission. Global datasets will likely continue to inform NFMS; however national input is needed to facilitate ownership of officially reported data and statistics.

Box 19: Relative efficiency

The ratio between the variances of the direct area estimate (based only on reference data) and the variances of estimates that rely on maps as auxiliary information gives relative efficiency (RE):

Equation 3

$$RE = \frac{V\hat{a}r(\hat{\mu})}{V\hat{a}r(\hat{\mu}_{Map})}$$

The same reduction in variance (i.e. increase in precision) could also be achieved by increasing the size of the sample in the reference data set by a factor of $n_1 = RE$.

Use of the map will be economically efficient if the cost of collecting the additional samples is greater than the cost of using the map in the project, given by:

Equation 4

$$n\,(n_1 - 1)\,p > M$$

where n is the original sample size of the reference data, p is the cost of acquiring each additional sample observation and M is the cost of producing the map. The break-even value of the map depends on the relative costs of producing the map and acquiring sample observations which will vary according to circumstances.

However, a map provides more than an improvement of the statistical precision. Additional information on the location of the forest and other land uses is provided and the map may also be used to carry out other tasks, subject to the accuracy of the map. The value of this additional information must also be taken into account when assessing overall economic efficiency.

Although they may not be representative of all cases examples of relative efficiencies obtained for national and global maps for a limited number of forest types are given in Appendix E, which suggest the following conclusions about the reference data sample size needed to achieve the level of precision required, subject to other constraints such as having sufficient observations within individual activity classes:

▸ Use of national rather than global maps can reduce the reference data sample size by 70% to 90% for area estimation, and by 50% to 80% for area change estimation (Appendix E, Table E1).

▸ Compared with using with reference data sample alone, use of a national map to estimate forest area can reduce the sample size by over 95% whereas use of global mapping can reduce sample size by 85% to 95%. When assessing change in forest area the same study suggests a 10% reduction in sample size when national mapping is used, and no reduction from the use of global maps However, this is likely to be due to the very low level of change observed during the 2000-2010 period, a 62% reduction in sample size is observed when the national map is used during the 1990-2000 period (Appendix E, Table E2)

▸ Use of global maps uncalibrated to local conditions in estimating forest area can reduce sample size by between zero and 35% whereas use of maps calibrated to national forest definition can reduce sample size by 30% to 50% (Appendix E, Table E2).

The relative efficiency of using remotely sensed data depends on many factors , e.g. the type of estimate being made (different activities – area estimates, different emission/removal factors), type and structure of the forest or the properties of the change and type of remotely sensed data. Generally, the more the property being estimated correlates with the remotely sensed data, the higher the relative efficiency is likely to be. This is an area where more research is needed.

4.2   Ground-based observations

Ground-based observations are needed for the estimation of carbon and non-carbon dioxide GHG emissions and removals for REDD+ activities, regardless of the sampling or inferential method used. Ground-based observations are used to estimate emissions and removals factors, establish growth models for different types of forests, to parameterise Tier 3 models and as reference data for estimating activity data. Although availability will differ from country to country, examples relevant ground-based observations include:

▸ NFIs, subnational forest inventories, and forest assessments based on plot or transect measurements;

▸ growth and yield studies, harvested wood removals, and models for converting these to biomass;

▸ auxiliary spatial data on land use, management, disturbance history, soil type which can be used to guide the selection and application of emissions and removals factors ;

▸ research data that can be used to estimate emissions and removals in above- and below ground biomass, litter, deadwood and soils;

▸ field observations which can be converted to emission/removal factors for non-CO_2 GHGs from soils and fire.

For REDD+, emissions and removals estimates can be developed using data from NFIs and related intensive monitoring sites and auxiliary data. In general it will be efficient for the NFMS to collate relevant existing information (1) prior to commencing any further sampling, and to conduct a gap analysis to determine the most efficient sampling strategy. Access to original data sets, data collection protocols employed as well as documentation of data quality checks undertaken are important for transparent reporting and assessment of generated estimates. To maintain representativeness, consistency of definitions and protocols, data generally need to be stratified according to forest type, soil and climatic conditions, topography, and the nature of forest disturbances induced by anthropogenic or natural factors (Chapter 2, Section 2.3.2).

4.2.1 National forest inventories

Most countries hold at least some NFI data that can be used to support emissions estimation for REDD+. Well-designed NFIs are based on probabilistic samples with well-understood statistical properties which helps estimation of confidence intervals. NFIs are a valuable source of information for emissions and removals estimation, particularly with respect to above-ground biomass, and by extension below ground biomass. Though traditionally established for forest resource assessment, most NFIs, (often in close collaboration with forest research institutions) also gather information on ecosystem-related variables, and through field-based interviews may help provide information on drivers of forest change. Participation in an NFI provides excellent experience with the challenges and practicalities of forest monitoring, and NFI field experience is extremely useful in understanding the relationship between ground-based and remotely sensed data.

As well as biomass, NFIs increasingly include the dead wood pool, and some have started to acquire information on soil organic carbon and litter, although measuring temporal change in these pools is challenging. Where the sampling design is suitable (or can be augmented) NFIs can be used to estimate REDD+ activities directly. Nevertheless:

▸ existing NFI sampling designs are unlikely to be optimized to estimate REDD+ activities such as deforestation or forest degradation, which thus increases uncertainties in estimating emissions and removals, and could require augmentation of the sampling as discussed below.

▸ although NFI sample plots are usually geo-located, and can provide useful indication of where sampling should be intensified, they generally do not deliver information sufficient [133] to track REDD+ drivers or to direct policy responses to deforestation or degradation.

▸ although an NFI for an entire country might be desirable, it is often logistically complex and expensive in large countries, especially those with large areas of non-commercial forest. It may also take 10 years or more to establish a complete NFI time series. Alternatives to estimating change during this period need to be considered when designing a NFI based system to monitor and estimate the GHG outcomes of REDD+ activities.

Tropical forests differ significantly from temperate forests in terms of diversity of tree species, the presence of very large trees, and the rate of recovery after forest disturbance. This makes it more challenging to estimate forest biomass, and change in biomass, across spatial scales ranging from local to

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[133] Although NFI data can be used to satisfy criteria for Approaches 1 and 2 to land representation (chapter 2.3.2 of GPG2003), sampling intensities rarely exceed 1 plot/km^2 (Tomppo et al., 2010, Table 2.3), which is very low spatial resolution. Effective tracking of REDD+ activities on the ground requires a higher spatial resolution than 1km^2.

landscape, region and national. Forest inventory experience is much less in the tropics than in temperate forests (Burslem & Ledo, 2015; Saatchi, 2015). These authors in their review of inventory experience in tropical forests provide useful guidance relating to the design and conduct of inventories for biomass, coarse wood debris and soil carbon. They highlight the limitations of earlier inventories and identify pitfalls to be avoided. They stress that approaches need to be adequate to deal with the very high spatial variability in mature forests and those recently disturbed by logging or fire. Young regenerating natural forests and plantations contain less biomass and are more homogeneous, thus simplifying the inventory task. The reliability of biomass estimates is lower at finer spatial scales.

NFI data directly estimate carbon stock change and can also be used to support the gain-loss method. Firstly, observations of biomass and carbon change on NFI plots between points in time can be used to estimate emission and removal factors, or help develop Tier 3 models of forest growth, debris and soil carbon. Secondly, under appropriate sampling designs, NFI plot-level land use and land-use change data can provide estimates of areas of particular land-use change categories. Thirdly, where models are used to enhance estimation of REDD+ activities, NFIs plus existing data can be used in model establishment and model verification.

Typically NFIs consist of an array of plots (or clusters of sub-plots) established in a systematic fashion across entire countries. Plot size is generally in the range 0.01 to 1 ha. For tropical inventories plots may need to be as large as 1 ha to reduce potentially large variance due to large variability rather than increasing the number of plots and associated costs. Larger plot sizes also help make the link to remotely sensed data. Observations and measurements on these plots vary but always include amount of forest cover and sufficient tree-level data such as species, diameter, and height which can be used with allometric models to predict volumes and biomass of individual trees (Lawrence et al., 2010). The tree-level predictions are aggregated to estimate plot-level tree volume or biomass and carbon stock. In addition, NFIs often acquire data on tree and shrub species diversity and general topography. Less commonly, observations or measurements will also include aspects of litter and other dead material, site history [134], soil, and canopy characteristics. These NFI data are typically used to estimate forest population parameters – including production or development related - at a precision considered relevant to national level planning, taking cost and NFI practice into account.

When measurements on the same plots are obtained at multiple points in time, annual change (and associated carbon change) can be estimated for each plot [135]. The timing of plot re-measurements within an NFI varies from only a couple of years in fast growing environments to 5-10 years in slower growing environments. Frequency may be less for environments that are more expensive to access and measure or for forests with low commercial value. A proportion of all plots may be measured each year so that the entire system is measured over a 5-10 year period. In an interpenetrating panel system, plots measured in any particular year (a panel) are systematically intermixed with plots measured in other years (panels) so that estimates for the entire area may be obtained each year. Heikkinen et al., 2012, describe methods for making more precise estimates using panel data and other data.

NFIs commonly use probability sampling in the form of simple random, systematic, or stratified random sampling designs. Probability sampling requires that each potential plot location has a probability greater than zero of being selected for the sample and that a randomization scheme is used to actually select the sample. The resulting data are used with unbiased estimators to calculate estimates of totals, changes and variances. Estimates for sub-sets of the original forest area are possible if sufficient plots can be

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[134] For example, evidence of past disturbance.

[135] Use of permanent plots increases precision of change estimation – see section 5.3.3.3 of GPG2003.

grouped into domains or strata and all points within the domain have a probability greater than zero for inclusion in the original sample. The number of plots required depends on variability of the population, the precision required, and the need to estimate rare events, such as deforestation. Increases or decreases in the area considered forest could violate design-based sampling principles and thus compromise the unbiased nature to the estimators. This problem may be avoided by expanding the NFI design to other land use types, and unless this is done the NFI will not be sensitive to afforestation or reforestation, and will always detect loss of forest area.

If the NFI plots were distributed using a systematic grid, the same grid spacing can be used to extend the sample into areas that were not included in the original NFI (e.g., to include forests on privately managed land or within land classified as crop- or grazing land or, settlements where they meet the adopted definition of forest). Similarly, intensification (increasing the number of plots per unit area) can be implemented to improve estimates in areas of particular interest (e.g. where change (deforestation or degradation) is happening or likely to happen.) In addition, estimates based on data from independent probability sampling designs can be combined to produce more precise estimates. If the boundaries of areas of interest change over time, it can become very complicated with repeated measurements to manage selection probabilities of plots in dynamic strata. For this reason if pre-stratification of the study area for variance reduction is performed, the stratum boundaries should be defined by features that do not change such as ecoregions, topography, or climate zones, or well-defined socioeconomic factors such as access to infrastructure (Box 20: Stratification and statistics).

Where NFI data are (or can be) grouped according to strata being used for REDD+ estimation they are likely to be valuable sources of data to estimate emissions/removals factors for REDD+ activities, or to develop Tier 3 models of forest growth, debris and soil carbon. If the land area associated with the NFI does not correspond spatially with the area of land to which the MRV is meant to apply, or if the NFI is not well-designed, the use of NFI data for the MRV could be called into question. In these cases, it might be more appropriate to use the NFI data for calibration and verification of remote sensing maps, or other estimation procedures like model-based estimation, in which case the data may be used purposively to parameterize models that are then used to make inferences, rather than basing inference directly on a probability sample.

Properly implemented, NFI-based methods satisfy Tier 3 requirements for above-ground biomass as set out in the GPG2003. Long-established NFIs are well-documented with respect to the validity and completeness of the data, assumptions, and models. Although new tropical NFIs do not have such long histories, and may face additional difficulties with locating and re-measuring plots in hard-to-reach areas, lessons learned from forest inventories in non-tropical countries can be used to improve sampling designs, field protocols, and statistical estimators.

Box 20: Stratification and statistics

In statistics, stratification subdivides a population into sub-populations, called *strata*, for two primary purposes, namely to:

▸ identify important sub-populations such as primary versus modified natural forest or deforested versus undisturbed forest area for which separate estimates are required,

▸ reduce the uncertainty of estimates for population parameters and/or selected sub-population parameters.

The two purposes are not necessarily mutually exclusive.

Stratification as a process aggregates individual population units such as forest stands or image pixels into strata. If the primary purpose of stratification is reduction of uncertainty, then population units assigned to the same stratum should be more similar to each other than to units assigned to other strata.

Two approaches to stratification are common, one characterized as stratified random sampling (also called pre-stratification) and the other characterized as post-stratification. The primary distinction between the two approaches is whether the sampling depends on, or is independent of, the stratification.

With stratified random sampling, the stratification is established before the sampling, primarily so that desired within-strata sampling intensities, and hence within-strata sample sizes, can be ensured. Therefore, in this case, the sampling depends on the stratification. As an example, greater sampling intensities may be desired for forest land subject to human activities than for remote and inaccessible forests generally not subject to human activities. As a second example, stratified random sampling can ensure sufficient sample sizes to achieve desired levels of precision for strata defined by rare activity classes such as deforestation (Olofsson et al., 2013). Under these circumstances, the stratification should be established before the sampling so that sufficient with-strata sample sizes can be ensured. Within-strata sample sizes for stratified random sampling are fixed because they are determined prior to the sampling.

With post-stratification, the sampling is conducted independently of and often before the stratification is imposed. Therefore, because stratified random sampling is not possible, the sampling intensities cannot be varied to accommodate desired within-strata sample sizes. An example is an NFI that uses a combination of permanent plots and a sampling design that does not change over time. One result is that sufficiently large within-strata sample sizes cannot be ensured. Nevertheless, stratifications imposed independently of (often subsequent to) the sampling can still increase the precision of population estimates. For example, if sampling intensities and/or strata sizes are sufficiently large, then the within-strata sample sizes may still be large enough to produce sufficiently precise within-strata estimates (McRoberts et al., 2013). Further, if the strata are relatively homogeneous, then the within-strata variances will be smaller than the overall population variance with the result that the uncertainty of the population mean will be reduced. Within-strata sample sizes with post-stratification depend on the sampling design and the stratification imposed and are generally not known beforehand.

The stratified random sampling and the post-stratified estimators of the population mean are identical and are unbiased in the sense that on average, over all possible samples, the estimate of the population mean will equal the true value. However, the estimate obtained with any particular sample may deviate substantially from the true value. One consequence of the fact that the sample sizes are fixed with stratified random sampling, but unknown initially with post-stratification is that the variance estimators differ slightly (Cochran, 1977, 134 (Eq. 5A.40).

4.2.2 Intensive monitoring sites

Intensive monitoring sites such as long term ecosystem research projects and national or even regional research observational and experimental plots can provide useful data sets for developing estimates of change in carbon density following land use changes. Unlike statistically based forest inventories, intensive monitoring sites generally use purposely selected sites and these networks of plots commonly consist of few (sometimes only one) large plots where the focus is on ecosystem functioning and processes. These typically have a long history of repeated measurements of a common and comprehensive suite of ecological variables relevant to producing estimates of emissions and removals, to a greater level of detail than may be available from extensive statistically based forest inventories alone.

Data from intensive monitoring sites can be used to develop emissions and removals factors or to parameterize models to scale-up estimates to regional and national levels when combined with remote sensed and national forest inventory data. Typically intensive field observations are used to assess effects of individual REDD+ activities and natural disturbances on above- and below-ground biomass, litter, deadwood and soil organic carbon pools. To be useful original data sets (not just means and distributions) should be available and data collection protocols documented and data quality checks undertaken. These characteristics are important for transparent reporting and assessment of generated estimates.

Intensive monitoring sites can be part of the ground data referred to in the decision tree on national choices in emission and removals estimation (Figure 13: Guidance on choosing inference framework for estimation of emissions and removals factors). To be useful, data collection at these sites should be harmonized as described in the notes for decision point 3 in the decision tree. They may facilitate inclusion of below-ground biomass using country-specific data rather than generic root-to-shoot ratios, and help with inclusion of non-biomass pools, and the inclusion of non-CO_2 gases. This information may be used to supplement data and information necessary to transition to higher tiers in MRV systems. These sites can provide detailed information about physiological parameters to develop and test models of carbon exchange, and to relate carbon fluxes to remote-sensing data. Data collection and analysis are combined across multiple spatial and temporal scales, with intensive and detailed studies providing specific information to scale-up through the use of remote-sensing techniques, extensive forest inventories and empirical and process modelling (Birdsey et al., 2013).

4.2.3 Auxiliary data

Auxiliary data are data often made available through the NFMS, National Forest Inventories or other national resources agencies which can play an important role in estimating emissions and removals from REDD+ activities by providing additional context for detected (or predicted changes). Auxiliary data sets can also come from neighbouring countries where similar forest types exist where there is an

absence of country specific data[136]. Auxiliary data may include disturbance histories, land tenure, forest management plans, harvest statistics, fire area data, wood fuel extraction data (or rate of wood energy for cooking), forest health surveys and pest impact data. It can also include biophysical measures such as climate, soil type, elevation and slope.

[136] In the absence of National data, regionally relevant data can be a substitute. For significant sources and sinks, the collection of national specific data should be prioritised.

> **Box 21: Example of the use of auxiliary data**
>
> A common example of the utility of auxiliary data relates to logging, which could indicate deforestation, forest degradation or be part of sustainable forest management activities. In this case auxiliary data on the existence of sustainable forest management plans, the extent of their application and the location of concessions could help with interpretation.

4.2.3.1 Use of auxiliary data in emission and removal factors and models

National (and jurisdictional) datasets such as climate data, soil characteristics, topography, potential forest types, growing season characteristics and evapotranspiration data can provide valuable inputs to estimating emission and removals through the use of empirical or process models allowing for more frequent data estimates that may not be collected from NFI cycles per se or representatively derivate from intensive monitoring sites.

Such data sets are particularly useful in developing emissions and removals estimates for soil carbon, litter, deadwood pools through models (Chapter 3, Section 3.2).

Other auxiliary data, such as, harvest rates and operations and other commercial data sets, forest management plans, plans for road and other infrastructure, use of fuel wood for energy in local communities, fire events statistics are particularly useful for estimating changes in biomass pools.

4.2.3.2 Use of auxiliary data in REDD+ estimation

Combining activity data (areas of deforestation, afforestation/reforestation, forest degradation, improved forest management, areas undergoing carbon stock enhancement) with auxiliary data can inform the estimation of ground conditions and of the likelihood of future changes within these areas. Such auxiliary data could include, but are not limited to, biophysical data such as elevation, rainfall, slope, soil type, etc. as well as data related to land use such as locations of existing forest plantations, charcoal-producing regions, roads, protected areas, previously burned areas (and frequency of forest fires), forest communities, areas under agricultural production, transport infrastructure etc.[137]

For the purpose of deforestation and degradation estimation all such auxiliary data should be spatial in format so that specific instances of deforestation or degradation can be linked to factors active in a specific stratum or location. Modelling potential deforestation or degradation location can be a cost effective way to target early warning monitoring and the strategic use of high resolution imagery.

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[137] Statistical models that classify the risk of disturbance utilising such auxiliary data are available (see Geomod/ IDRISI, Land Change Modeler, Dinamica. Alternatively countries can develop their own which are typically linked to Tier 3 integration frameworks (see Chapter 3, Section 3.2).

4.3   Guiding principles – Remote sensing and ground-based observations

▸ In most cases estimates of emissions and removals associated with REDD+ activities will be made using a combination of remotely-sensed and ground based data.

▸ Landsat satellites provide a time series of remotely sensed digital images spanning 40 years and are being used widely in monitoring activities such as deforestation, forest degradation and natural disturbances, and for estimating changes in biomass and carbon stocks.

▸ Other types of remotely sensed data, such as SAR, LIDAR and high resolution optical data are increasingly available and helpful especially in extending the range of REDD+ activities for which operational methods are available.

▸ Pre-processed data sets can be used as a basis for REDD+ estimation in conjunction with reference and auxiliary data to capture national circumstances.

▸ Remotely sensed and auxiliary ground-based data in combination are likely to be useful for stratification in order to increase sampling efficiency.

▸ If sufficient NFI data are available over space and time and at sufficient spatial resolution, NFIs can be used to estimate directly from repeated inventories stock changes associated with REDD+ activities. It will often be best to use NFIs in combination with remotely-sensed data.

▸ Data from NFIs are also a potentially valuable source of information for REDD+ estimation using gain-loss methods, and for developing modelling approaches at Tier 3.

▸ Detailed information generated at a fine scale at intensive monitoring sites can help address the difficulty of estimating stocks and stock changes for litter, dead wood and soil, by supporting development of model parameters, including emissions and removals factors.

Chapter 5 Estimation and uncertainty

This chapter sets out activity data and emission factor requirements and exemplifies statistical inference methods for their estimation using unbiased estimators consistent IPCC definition of *good practice* and for use in the methods outlined in Chapter 3. These methods remove the expectation of bias and quantify uncertainties. Methods for combining uncertainties to generate an overall uncertainty estimate are provided, building on IPCC guidance. Guiding principles given at the end of the chapter summarise aspects that may help a country decide on the combination of data sources and methods used to support reporting on GHG emissions and removals.

5.1 Activity data

The description of REDD+ activities and the discussion of the use of IPCC methods to estimate emissions associated with them (Chapter 3, Section 3.1) lead to the activity data requirements specified in Table 13: Major activity data requirements for REDD+ activities.

Table 13: Major activity data requirements for REDD+ activities

Row	Data requirement
1	Areas of *primary forest*, *modified natural forest*, and *planted forest*[a], sub-stratified as necessary by forest type and management regime.
2	Annual conversion from *primary forest*, *modified natural forest*, and *planted forest* to non-Forest Land uses (Cropland, Grassland, Wetland, Settlements, Other Land)
3	Annual transfer from *primary forest* to *modified natural forest* and *planted forest.*
4	Annual transfer from *modified natural forest* to *planted forest*
5	Annual conversion from non-Forest Land uses to *planted forest* or natural expansion within managed land areas
Notes: a)These are the forest types used in the methodological discussion because they correspond to reporting to the FRA. Countries may adopt other stratifications which suit national circumstances.	

5.1.1 Methods for estimating activity data

For estimating activity data, maps serve multiple purposes. First, subject to classification error, they depict the general spatial distribution of land attributes in general and forest resources in particular. Second, maps that depict forest-related classes or that can be aggregated or converted to forest-related classes can serve as the basis for stratification. Maps depicting forest classes and particularly forest change classes can be used to support construction of stratified sampling designs for purposes of estimating activity data. Third, maps of continuous variables such as percent forest canopy cover and even biomass can be used directly with model-assisted methods to estimate rates of forest change and can be aggregated to produce forest class maps.

Factors that influence a country's decisions concerning which data and methods to use for assessing activity data include the nature of the forests in the country, forest management practices, availability of various kinds of satellite data, existing satellite image analysis capabilities, availability of ground-

based data and general level of technological capacity. Spatial resolution, annual observations of forest disturbances, and attribution of land-cover changes by disturbance type all influence activity data uncertainty (Mascorro et al., 2015).

5.1.2   Maps of forest/non-forest, land use, or forest stratification

At the heart of the use of remote sensing images is the translation of the remotely sensed measurements into information about surface conditions (land cover) and then some additional information to enable the translation of land cover to land use for reporting consistently with IPCC categories. Generating the various kinds of activity data necessary for estimating GHG emissions and removals involves categorization of lands. Ideally countries would develop maps with categories that best suit their conditions and broad national and international reporting requirements. These country specific categories would then be represented as the corresponding IPCC categories through the application of country specific rules to enable reporting to these IPCC land use categories through time.

For example, for estimation of forest area changes, a map is usually made that includes the categories *forest* and *non-forest*[138]. To correspond to the top-level categorization adopted by IPCC GPG2003, the map would need to have at least the following categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. There may be need to stratify forest areas according to ecosystem types or other nationally relevant categories for a range of reasons, for example broader NFMS reporting requirements or to minimize the variability in carbon content. Consequently, methods that define categories, or classes, using remote sensing and attribution are particularly relevant. Collectively, these methods are referred to as image classification, and there is a long history of their use in remote sensing. There has also been extensive research on the best methods for image classification and as a result a wide variety of choices are available. Most image processing packages include several algorithms for image classification. Common image classification algorithms include maximum likelihood, decision trees, support vector machines and neural networks. Many of these are available in standard image processing software packages[139].

Image classification begins with the definition of the categories or classes to be included in the map. In supervised classification, it is necessary to provide training samples of each of the classes to be included. These samples could come from a variety of sources, including sample sites from an NFI, or could be obtained from high resolution images. For the basic classes of *forest/non-forest*, or the small number of top-level categories used by IPCC GPG, examples can often easily be found in the images being classified. Often images from a single date are used for image classification. However, multiple images from different seasons can also be used in image classification to try to capture classes with seasonal dynamics. As the level of stratification of forests increases, alternative sources of reference data to train classifiers will be needed, such as prior vegetation maps or field plots.

Classification can be done by visual interpretation, but this can be very human resource intensive[140] because the number of pixels may be very large and interpretations can vary due to human judgement. This may be overcome by using automated algorithms in either non-supervised or supervised approaches to give results consistent with human interpreters in allocating a pixel to one forest type or another, or to segment the data. Non-supervised approaches use classification algorithms to assign image pixels

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[138] Italics are used here to indicate names of *categories* (also called *classes*) in a map.

[139] Packages include Orfeo, QGIS and GDAL.

[140] See section 2.1 of the GOFC-GOLD sourcebook.

into one of a number of unlabelled class groupings. Expert image interpreters then assign each of the groupings of pixels a value corresponding to the desired land class. Supervised approaches use expertly-defined areas of known vegetation types to tune the parameters of classification algorithms which then identify and label areas similar to the input training data. The approaches have different challenges which are best addressed by iterative trials: supervised classification may wish to use more classes than are statistically separable; unsupervised methods may generate fewer classes than are desired and a given cover type may be split between several groupings. In both cases human interpreters can check whether the results of applying the algorithm appear reasonable in terms of the forest type distribution expected from prior information, and result in the absence of unlikely features. The relative advantage depends on whether the time taken in checking automatic classifications exceeds the time taken to achieve consistent results by relying entirely on human interpreters.

Rarely does the first attempt at image classification result in the final map. Close examination of the classification results often reveals issues and problems that can be resolved by changes in the classification process. There are many ways to try to improve the results of a classification with noticeable problems, including the addition of more or improved training data. It may also be helpful to include additional kinds of data in the classification, such as topographic or climatic data.

Recognition of various strata of *modified natural forests* will generally need to take account of surrounding pixels because features such as crown cover disturbance, fragmentation or logging infrastructure will not occur in every pixel of the area affected. Consequently, when considering the boundary between *modified natural forest* and *primary forest* it will be necessary to establish a radius within which evidence for modification is taken to be relevant to the pixel in question. If pixel based classification is to be used subsequently the radius is used directly; if the pixels are first to be segmented (grouped according to common properties) it becomes an input to the segmentation process (Box 22: Pixel and object-based methods and segmentation).

Conceptually this radius is the distance needed to regain the characteristics of primary forest, represented for REDD+ purposes. A default of 500 metres can be used, but the value will depend on forest ecosystem and type of modification, and is best established by measurement[141], especially if using an IPCC Tier 2 or 3 method. If the result of using a particular radius of influence is that fragments of nominally primary forest appear along the boundary between primary and modified natural forest, then the radius of influence being used is probably too small. This is because forest within a fragmented landscape is more likely to be *modified* than *primary*. Having established image characteristics of forest types and the radius of influence it is possible to assign a forest type (and sub-strata) to each pixel for the entire forest area of the country, as described above.

Attribution integrates remote sensing data, forest inventory and ancillary datasets to attribute the land-cover change observations to the most likely disturbance type (natural or anthropogenic). Typical data sets used in attribution include those with information relating to fires, forest management areas, agricultural areas, road coverage and urban areas (Mascorro et al., 2015). As satellite-based algorithms detect increasingly diverse change processes, the need to distinguish among the agents causing the change becomes critical. Not only do different change types have different impacts on natural and anthropogenic systems, they also provide insight into the overall processes controlling landscape condition. Reaching this goal requires overcoming two central challenges. The first is related to scale mismatch: change detection in digital images occurs at the level of individual pixels, but change

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[141] For example, work in Guyana using change metrics indicated that almost all the degradation associated with new infrastructure occurs within a buffer zone about 100 metres deep (Winrock International, 2012).

processes in the real world operate on areas larger or smaller than pixels, depending on the process. The second is related to separability: change agents are defined by natural and anthropogenic factors that have no connection with the spectral space on which the change is initially detected. Different change agents may have nearly identical spectral signatures of change at the pixel and even the patch level, and must be distinguished by factors completely outside the realm of remote sensing (Kennedy et al., 2014).

Box 22: Pixel and object-based methods and segmentation

Acceptable accuracies for land cover and land cover changes can be achieved using either pixel-based or object-based classification methods. Object-based methods first group together pixels with common characteristics, a process called segmentation. At medium resolution as defined here these can sometimes yield higher overall accuracies than pixel-based methods for land cover classification (Gao & Francois Mas, 2008). Segmentation is also useful for reducing speckle noise in SAR images prior to classification. However if the smallest number of pixels to be grouped (the minimum mapping unit) is too large there is a risk of biasing the classification results, e.g. if the MMU is to large then an area could be counted as deforested on the basis of reduced crown cover even if it contained areas still meeting the national forest definition. In practice the minimum mapping unit should not exceed the smallest object discernible in the imagery.

Image segments provide an advantage when part of a processing chain requires human interpreter input. This is because image segments can be combined into larger polygons which can be more easily reviewed and revised for classification errors (FAO & JRC, 2012). Tracking change at the pixel level opens the way to better representation of carbon pool dynamics, however it requires significantly more data processing.

Pixel-based approaches are potentially most useful where there are multiple changes in land use within a short period (for example, 10-15 year re-clearing cycles). They are most suited when there is complete data coverage (sometimes referred to as *wall-to-wall*), and require methods to ensure time series consistency at the pixel level. The approach may also be applied to sample based methods where pixel-level time series consistency methods are used, with the results scaled up based on the sample size. The results may still be summarised in land use change matrices. In fact the method is equivalent to matrix representation at the pixel level (AGO, 2002).

In addition to the general principles of consistent representation of land when using remote sensing for representing land or tracking units of land using a pixel approach, MGD advice is that:

▸ Once a pixel is included, then it should continue to be tracked for all time. This will prevent the double counting of activities in the inventory and will also make emissions estimates more accurate.

▸ Stocks may be attributed to pixels, but only change in stocks and consequent emissions and removals are reported, with attention to continuity to prevent the risk of estimating large false emissions and removals as land moves between categories.

▸ Tracking needs to be able to distinguish both land cover changes that are land-use changes, and land cover changes that lead to emissions within a land-use category. This prevents incorrect allocation of lands and incorrect emissions or removals factors or models being applied that could bias results.

Rules are needed to ensure consistent classification by eliminating oscillation of pixels between land uses when close to the definition limits.

5.1.3 Detecting areas of change

Change detection is one of the most common uses of remote sensing, and many methods have been used, tested and proposed in the literature, although there is little information about which methods work best

in which situations. In general, at least two dates of images (end-points) are necessary to map change. Image classification methods are commonly used, in which case multiple images are used to make the assignment to stable classes (places that have not changed) as well as change classes, such as Forest to Grassland (Woodcock et al., 2001). Methods use the change in a spectral band, bands or indices as the basis of the change detection process (Lambin and Strahler, 1994). The GOFC-GOLD Sourcebook (GOFC-GOLD, 2015) includes descriptions and examples of several change detection methods[142] and is a useful resource when considering options for combinations of methods and remote sensing data to be used for mapping change.

Methods that use many images, or a time-series of images, have been developed and tested (Chen et al., 2004; Kennedy et al., 2007; Furby et al., 2008; Zhuravleva et al., 2013). These approaches have many advantages, as they are not so dependent on the conditions at the time the individual images were collected. Use of a time-series of images can help avoid some kinds of errors in the monitoring of forest change. Box 23: Time series analysis of earth observations for monitoring of activity data provides more detail on time series analysis.

Detecting change in land cover is not sufficient to map change in land use, which is needed for consistency with IPCC guidance. To make the distinction between deforested areas and areas where crown cover has been removed but forest land use remains (as needed for Row 2 in Table 13)[143], georeferenced areas of forest planted annually or allowed to regenerate naturally within managed forest should be obtained from national forest authorities and stakeholders via the NFMS. The existence of planted or regenerating forest on these areas confirmed as the appearance of the corresponding pixels merges with the appearance of other pixels with this forest type. This also applies to areas which may have the appearance of deforestation but which have in fact been subject to natural disturbance such as wildfires, cyclones, or pest outbreaks. Use of local information such as forest type and management intent, climatic extremes such as drought, and records of natural disturbance will be useful in aiding the translation of imagery into reliable activity data. Time series data (Box 23: Time series analysis of earth observations for monitoring of activity data) can also help make the distinction.

The methods described in Chapter 3, Section 3.1.2 for estimating GHG emissions and removals associated with degradation require stratification (or categorization) of forests into *primary*, *modified natural forest*, and *planted,* or another stratification used by a country. There may be sub-stratification to capture different forest ecosystems or types of human intervention. This can be achieved by a combination of remotely-sensed data (in most cases 30m resolution or finer) and supplementary data (such as concession boundaries, land use planning data and information on infrastructure).

Stratification plus reference data provides the activity data. NFI or equivalent field sampling possibly in combination with LIDAR or SAR data are used to identify carbon densities and long-term trends that provide the emission/removal factors needed. Stratification using remote sensing can also be used in the design of sampling strategies for the stock change approach. Methods to use remote sensing to map areas undergoing degradation or other change include use spectral indices (combinations of spectral bands designed to accentuate surface characteristics), spectral mixture analysis, and textural analysis. Visual methods can also be effective for stratifying forests on the basis of degradation. Examples of

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[142] See section 2.1 and 2.2 of GOFC-GOLD Sourcebook. In particular Table 2.1.3 lists the main analysis methods for medium resolution imagery.

[143] Such data are required as the existence of planted or regenerating forest on these areas requires confirmation as the appearance of the corresponding pixels merges with the appearance of other pixels with this forest type.

identifying degraded forest areas can be found in Winrock International, 2012; Souza et al., 2013; and Bryan et al., 2013.

Mitchell (2014) has provided a summary of evolving requirements and capabilities in forest degradation monitoring, based on the on the expert workshop on approaches to monitoring forest degradation organized jointly by GFOI, GOFC-GOLD and the European Space Agency in October 2013. Table 14: Useful data sources for use in combination to estimate emissions from degradation , based on table 5 in the workshop report, summarizes the use of different remotely sensed data sources in combination with ground-based and supplementary data to monitor processes that can lead to long-term decline in carbon stocks, either by transfer of forest areas from carbon strata from those with higher to lower carbon density, or (if the intensity of the activity increases) to decline of long-term carbon density within a given stratum. The relationship of these possibilities to degradation is discussed in Chapter 3, Section 3.1.2.

Table 14: Useful data sources for use in combination to estimate emissions from degradation

Process (d)	Activity Data	Emission/removal factors	Auxiliary Data
Tree removal – clear cut	Optical: 30m or better (a); SAR L (b) or C band (c)	**Sample based:** Repeated NFI or permanent plots (a)	Forest concession boundaries Land use plans Harvest estimates combined with growth estimates
Tree removal – selective with infrastructure	Optical: 30m or better (a); SAR L (c), C (c) or X (c) band	Field sampling: disturbed vs. undisturbed areas (a)	Settlements transport network (road, rivers) Data from local communities and stakeholders (f)
Tree removal – selective without infrastructure	Optical: 5m or better (b); SAR X (c) band	Terrestrial LIDAR (b) **RS combined with field observations (NFI or bespoke):**	
Forest area affected by shifting cultivation	Optical: 30m or better (a); SAR L band (b) or C band (c)	Height changes: airborne LIDAR (b), InSAR height differences (c)	Settlements transport network (roads, rivers) Forest concession boundaries
Fire – fire scars	Optical: 30m or better (a); SAR L band (b) or C band (c)	Backscatter derived AGB estimates (c)	Of possible relevance to assessing fire frequency or fuel load: Forest concessions boundaries Land use plans Settlements transport network (road, rivers)
Fires – ground fire	Optical: 5m or better (b); SAR X band (c)	VHR Optical texture based AGB model (c)	

Process (d)	Activity Data	Emission/removal factors	Auxiliary Data
Forest area affected by agroforestry	Optical: 5m or better (c)	**Sample based:** Repeated NFI or permanent plots (a)	Land use plans Settlements transport network (road, rivers)
Fuel wood and charcoal extraction	Mostly not detectable from RS	Field sampling: disturbed vs. undisturbed areas (a) Terrestrial LIDAR (b)	Population consumption per capita Forest growth potential GIS models
Forest grazing			Livestock estimates and consumption rates Forest growth potential GIS models
Forest regrowth following clearcuts, logging roads, fire scars (e)	Optical: 30m or better (b) SAR L band (b) or X band (c)	**Sample based:** Repeated NFI or permanent plots (a)	Previous disturbance from activity data

Reference: (Mitchell 2014, with modification)

Notes: a) The method is operational in countries; b) Large-scale demonstrations of the method exist; c) The methods have been demonstrated; d) These processes can lead to transfer of forest areas from strata with higher to lower carbon density, or (if intensified over time) to reduced carbon densities within given strata, which can be associated with degradation as described in Chapter 3, Section 3.1.2; e) Relevant to long-run carbon densities; f) Not repeated in every row, but of possible relevance in most cases.

Box 23: Time series analysis of earth observations for monitoring of activity data

A time series is a sequence of observations taken sequentially in time. Adjacent observations are typically dependent and time series analysis is concerned with techniques for analysis of this dependency (Box et al., 1994). In the context of activity data, each point in the series is interpreted in the same way as a single image (e.g. by visual interpretation or semi-automated algorithms) with the advantage that additional information can be obtained by considering the series as a whole.

It is useful to distinguish between two or a few images over a study period (e.g. 10-15 years) and an annual or higher frequency of observations. It is easy to imagine that having many observations of the land surface rather than just two snapshots in time allows for a more comprehensive analysis of surface activities. Yet, traditional image analyses of land cover and land change have often relied on few images because of the cost of acquiring suitable imagery. The opening of the Landsat archive in 2008 (Woodcock et al., 2008) relaxed this constraint, and a time series of Landsat observations (with an 8-16 day revisit time) can be obtained for virtually any place on Earth. Other data sources are available but the combination of a free, open and extensive archive with the temporal and spatial characteristics of Landsat data makes it a highly useful for time series analysis.

Time series analysis allows tracking activities rather than creating a map that represents conditions at one point in time or a change map between two points. It enables characterization of post-disturbance landscapes and gradual and continuous activities such as regrowing forest and forest degradation. In the following example (adapted from Kennedy et al., 2014), a forest was cleared and then allowed to regenerate. In the figure below only 2 observations in time are available in (a), 5 in (b), whereas a dense time series is available in (c) that allows for an accurate representation of the activity.

With just two observations (a) it appears as if the land surface variable (which could be a surface reflectance, backscatter or a vegetation index) being observed is showing a slight decrease. The situation is improved with several observations available (b) that provide some evidence of the disturbance event and the subsequent recovery. Still, the land surface activities are not readily identified nor are the timing of events. With many observations (c) the analyst can determine the timing and magnitude of the logging event and characterize the recovery in time and space. Provided that the carbon content of the forest that was logged and carbon dynamics of the recovering forest are known, the analyst could estimate the amount of carbon emitted from both the soil and decomposing logged wood, and the amount carbon sequestered in the recovering forest and soil following the logging event. Examples of operational systems that use this method include Canada, Australia and Indonesia (see Appendix C), all of which use the integration tools detailed in Chapter 3, Section 3.2.
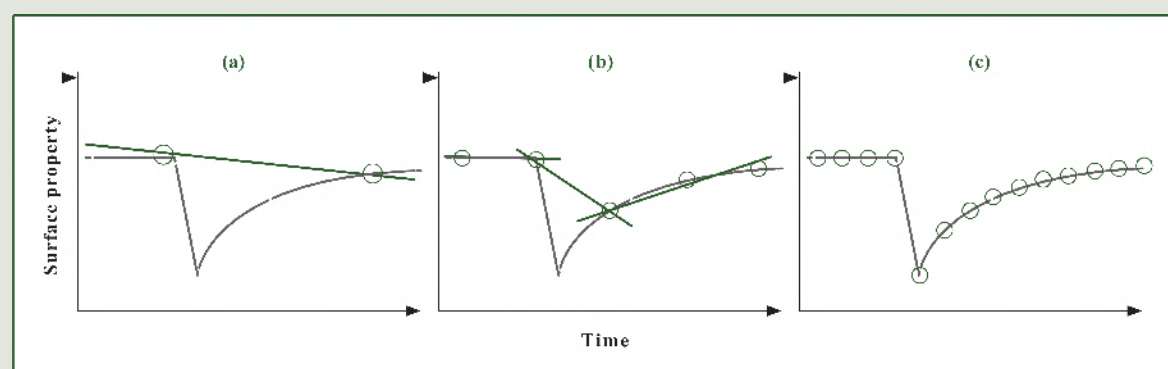
To achieve the results illustrated the figure above, it is possible to create pixel-level composites by applying a statistic (median or max value for example) to a fixed number of observations, select the best images according to some criterion (growing season, minimum cloud cover, etc.), or try to use all of available observations. Composites and "best images" approaches have the advantage of reducing the amount of data to be analysed but information on land activities is reduced compared to an "all observations" approach. The latter enables a detailed analysis of the landscape but requires considerable storage and computing capabilities.

Composite-based approaches have proved successful for large scale change mapping and been used for making global maps of tree cover change at annual basis (Hansen et al., 2013). The same is true for "best images" approaches, which have been used for creating global change maps at five year interval (Kim et al., 2014). The latter has the advantage of reduction in data volume which allows algorithms to faster process the data which in turn enables the analyst to revisit the training data and redo and refine the classification process more often. Several composite-based algorithms for change detection have been published since the opening of the Landsat archive (e.g. Griffiths et al., 2014; Huang et al., 2010; Kennedy et al., 2010) and cloud computing platforms such as Google Earth Engine can be used to create composites for large areas without downloading the data. If having direct access to the satellite data, the BEEODA virtual machine contains open source algorithms for compositing.

While composite-based methods are powerful, the reduction of data also implies that there are observations of the area of interest that are not being used. Algorithms such as CCDC (Holden, 2015; Zhu et al., 2012; Zhu & Woodcock, 2014b) and BFAST (Verbesselt et al., 2010; Verbesselt et al., 2012; DeVries et al., 2015) are examples of change detection algorithms that analyses all available observations. The approach is more computationally intensive and requires detailed screening for clouds and cloud shadows but it enables a more comprehensive analysis of the land surface. It allows for studies of phenology and seasonality, and for a more detailed analysis of post-disturbance landscapes, especially dynamic landscapes that exhibit rapid change.

Use of archives other than Landsat will grow in future as the archives of other satellite missions develop, and as new free data missions are launched. For example, the Sentinel-2 mission will generate data that when combined with Landsat data will enhance time series analysis of the land surface. SAR data, which can provide more stationary time series because of cloud penetrating capabilities, are also likely to enhance the analysis when combined with optical data (Reiche et al., 2015). Time series analysis of radar alone is now facilitated with the advent of Sentinel-1 data that is available free of charge. Although both CCDC and BFAST (Verbesselt et al., 2012; Xin et al., 2013) have been used with coarse resolution data (MODIS) for near real time monitoring of forest disturbance, these data are not usually used for mapping activity data because of their coarse spatial resolution.

Time series make reference data collection somewhat more complex and time consuming, which may result in a smaller sample size, but with tools such as TimeSync (Cohen et al., 2010), BFAST Spatial and TSTools the collection of temporal reference observations is possible. A suitable approach is to collect annual reference observations enabling computation of annual unbiased estimates and confidence intervals (Cohen et al., 2016).

5.1.4 Additional map products from remote sensing

Remote sensing can also be used to provide a variety of products that may be helpful to countries for forest management. Even simple maps that show the distribution of forests can help visualize change in forest area through time. Maps of land use beyond the six IPCC categories discussed in Chapter 2, Section 2.3.2 can inform decision making related to land management activities. Similarly, detailed maps of forest types, or strata, are an integral part of many forest planning and management activities. Near-real time maps of forest change (Xin et al., 2013; Verbesselt et al., 2012) can be used to help minimize illegal logging and to reduce encroachment of deforestation on protected areas.

5.1.5 Estimating uncertainty of area and change in area

The IPCC definition of good practice requires that emissions inventories should satisfy two criteria: (1) neither over- nor under-estimates so far as can be judged, and (2) uncertainties reduced as far as is practicable (IPCC, 2003; preface).

In statistical terms, the first criterion is closely related to the statistical concept of bias. Bias is a property of a statistical formula called an estimator which, when applied to sample data, produces an estimate. An estimator is characterized as unbiased if the average of all estimates calculated using data for all possible samples acquired using the sampling design equals the true value of the parameter of interest; otherwise, an estimator is characterized as biased. In practice, application of the estimator to all possible samples is impossible, so that bias can only be estimated, and an estimate obtained using an unbiased estimator may still deviate substantially from the true value; hence, the concept of confidence interval. A confidence interval expresses the uncertainty of a sample-based estimate and is formulated as a sample-based estimate of the parameter plus/minus the sample-based estimate of the standard error of the parameter estimate, multiplied by the confidence level. Confidence intervals at the 95%-level are interpreted as meaning that 95% of such intervals, one for each set of sample data, include the true value of the parameter. The width of a confidence interval is closely related to precision, a measure of the uncertainty addressed by the second IPCC criterion. Confidence intervals constructed using unbiased estimators therefore satisfy both IPCC good practice criteria specified above. This section provides advice on how to use such estimators to infer central values and confidence intervals for activity data.

Methods that produce estimates of activity data as sums of areas of map units assigned to map classes are characterized as *pixel counting* and generally make no provision for accommodating the effects of map classification errors. Further, although confusion or error matrices and map accuracy indices can inform issues of systematic errors and precision, they do not directly produce the information necessary to construct confidence intervals. Therefore, pixel-counting methods provide no assurance that estimates are "neither over- nor under-estimates" or that "uncertainties are reduced as far as practicable". The role of *reference data*, also characterized as *accuracy assessment data*, is to provide such assurance by adjusting for estimated systematic classification errors and estimating uncertainty, thereby providing the information necessary for construction of confidence intervals for compliance with IPCC good practice guidance.

Direct observations of ground conditions by field crews are often considered the most reliable source of reference data, but interpretations of aerial photography and satellite data are also used. When the source of reference data is not direct ground observations, the reference data must be of at least the same and preferably of greater quality with respect to both resolution and accuracy than remote sensing-based map data. For accuracy assessment and estimation to be valid for an area of interest using the familiar design- or probability-based framework (McRoberts, 2014), the reference data must be collected using

a probability sampling design, regardless of how the training data used to classify for example a satellite image are collected. Probability sampling designs to consider are simple random (SRS), systematic (SYS), stratified random (simple random sampling within strata) or systematic (systematic sampling within strata) (STR), and two-stage and cluster sampling. A key issue when selecting a sampling design is that the sample size for each activity must be large enough to produce sufficiently precise estimates of the area of the activity, given the policy requirement and the costs involved. SRS and SYS designs produce sample sizes for individual activities that are approximately proportional to their occurrence. If a very large overall sample is obtained, then SRS or SYS may produce large enough sample sizes for individual activities to produce estimates of sufficient precision. However, unless the overall sample size is large, sample sizes for activities representing small proportions of the total area may be too small to satisfy the precision criterion. Thus, given the likely rarity of some activities and the potentially large costs associated with large samples, serious consideration should be given to stratified sampling (STR) for which the strata correspond to map activity classes. With two-stage sampling, initial primary sampling locations are chosen, then several secondary sample units are selected within the primary sampling units. The motivation is often to reduce sampling costs but several factors must be considered when planning a two-stage sampling design. If distances between pairs of second-stage sampling units are less than the geographic range of spatial correlation, then observations will tend to be similar and the sampling will be less efficient. Further, the analysis of the sample is often more complex than if analysing a sample selected by SRS, SYS or STR designs. When dealing with continuous observations (such as proportion of forest) rather than classifying forest into classes or categories, model-assisted estimators may be more efficient. Typically, these estimators use the map predictions as the model predictions and then use a reference sample selected using an appropriate sampling design to correct for estimated bias resulting from systematic classification or prediction error.

Once a sample of reference observations has been collected, the activity area and the associated confidence interval are estimated using a statistical estimator corresponding to the sampling design.

5.1.5.1 Simple random and systematic estimators

The simplest approach to estimating the components necessary for construction of a confidence interval is to use the familiar SRS estimators of the mean, $\hat{\mu}_{SRS}$, and the variance of the estimate of the mean, $V\hat{a}r(\hat{\mu}_{SRS})$,

Equation 5

$$\hat{\mu}_{SRS} = \frac{1}{n} \sum_{i=1}^{n} y_i$$

and

Equation 6

$$V\hat{a}r(\hat{\mu}_{SRS}) = \frac{\sum_{i=1}^{n} (y_i - \hat{\mu}_{SRS})^2}{n(n-1)}$$

where i indexes the n sample observations and y_i is a reference observation. The primary advantages of the SRS estimators are that they are intuitive, simple, and unbiased when used with an SRS design; the disadvantage is that variances are frequently large, particularly for small sample sizes and highly variable populations.

5.1.5.2 Stratified estimators

When within-strata sampling intensities differ, STR estimators must be used. The essence of stratified estimation is to assign population units to groups or strata, calculate within-strata sample plot means and variances, and then calculate the population estimates as weighted averages of the within-strata estimates where the weights are proportional to the strata sizes. Stratified estimation requires accomplishment of two tasks: (1) calculation of the strata weights as the relative proportions of the population area corresponding to strata, and (2) assignment of each sample unit to a single stratum. When maps serve as the basis for strata, the first task is accomplished by calculating the strata weights as proportions of map units assigned to strata. The second task is accomplished by assigning sample units to strata on the basis of the strata assignments of the map units containing the centre of the location of the reference observation.

STR estimators of the mean, $\hat{\mu}_{STR}$, and the variance of the estimate of the mean, $Var(\hat{\mu}_{STR})$, are provided by Cochran (1977) as,

Equation 7

$$\hat{\mu}_{STR} = \sum_{h=1}^{H} w_h \hat{\mu}_h$$

and

Equation 8

$$Var(\hat{\mu}_{STR}) = \sum_{h=1}^{H} w_h^2 \frac{\hat{\sigma}_h^2}{n_h}$$

where

Equation 9

$$\hat{\mu}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi}$$

and

Equation 10

$$\hat{\sigma}_h^2 = \frac{1}{n_h - 1} \sum_{i=1}^{n_h} \left(y_{hi} - \hat{\mu}_h \right)^2$$

$h=1,\ldots,$ H denotes strata; y_{hi} is the ith sample observation in the hth stratum; w_h is the weight for the hth stratum; n_h is the number of plots assigned to the hth stratum; and $\hat{\mu}_h$ and $\hat{\sigma}_h^2$ are the sample estimates of the within-strata means and variances, respectively.

STR estimators may also be used with data acquired using SRS or SYS designs. For example, large area monitoring programs often use permanent plots whose locations are based on systematic grids or tessellations and use sampling intensities that are constant over large geographic areas. In such cases, even though stratified sampling is not possible, increase in precision may still be achieved by using stratified estimation subsequent to the sampling, a technique characterized as post-sampling stratification or simply *post-stratification* (PSTR) (Cochran, 1977, p. 135). With PSTR, the same estimator, Equation 7, is used for the mean, but the variance estimator includes a modification (Cochran, 1977, p. 135),

Equation 11

$$Var\left(\hat{\mu}_{PSTR}\right) = \sum_{h=1}^{H}\left[w_h\frac{\hat{\sigma}_h^2}{n} + \left(1 - w_h\right)\frac{\hat{\sigma}_h^2}{n^2}\right]$$

5.1.5.3 Model-assisted estimators

The essence of the estimators is that the relationship between a variable of interest such as crown cover and predictor variables such as map classes or spectral intensities may be used to predict the variable of interest (e.g. crown cover) for each map unit. The estimate obtained by adding or averaging all the map unit (pixel) predictions is then corrected for estimated bias resulting from systematic prediction error by comparing the reference and map data. Because the relationship is often estimated using a regression model, the estimator is characterized as the model-assisted, generalized regression (GREG) estimation. However, the estimators can be used with a large variety of methods for producing the map predictions, not necessarily involving regression (Sannier et al., 2014). The model assisted general regression estimators (GREG) are provided by Särndal et al., (1992, section 6.5) as,

Equation 12

$$\hat{\mu}_{GREG} = \frac{1}{N}\sum_{i=1}^{N}\hat{y}_i - \frac{1}{n}\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)$$

and,

Equation 13

$$Var\left(\hat{\mu}_{GREG}\right) = \frac{1}{n\left(n-1\right)}\sum_{i=1}^{n}\left(\varepsilon_i - \bar{\varepsilon}\right)^2 ,$$

where N is the number of map units, n is the reference set sample size, y_i is the observation for the ith reference set sample unit, $\hat{y}_i$ is the map class, $\varepsilon_i = \hat{y}_i - y_i$, and $\bar{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\varepsilon_i$. The first term in Equation 12,

$\frac{1}{N}\sum_{i=1}^{N}\hat{y}_i$, is simply the mean of the map unit predictions, $\hat{y}_i$, for the area of interest, and the second term,

$\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)$, is an estimate of bias calculated over the reference set sample units and compensates for systematic classification errors. The primary advantage of the GREG estimators is that they capitalize on the relationship between the reference observations and their corresponding map predictions to reduce the variance of the estimate of the population mean.

For continuous reference observations such as proportion of forest, the GREG estimators typically produce slightly greater precision than the STR estimators. However, when the map and the reference data represent the same classes of a categorical variable (such as activity classes), the STR estimators produce slightly greater precision than GREG estimators (McRoberts et al., 2016).

The decision tree in Figure 12. Guidance on choosing inference framework for estimation of activity data is intended to help users decide which sampling designs and estimators to use given the nature of the maps and available reference data. Decision point and subsection numbers in the following discussion correspond to the numbered decision points in the decision tree (Figure 12. Guidance on choosing inference framework for estimation of activity data).

Figure 12. Guidance on choosing inference framework for estimation of activity data
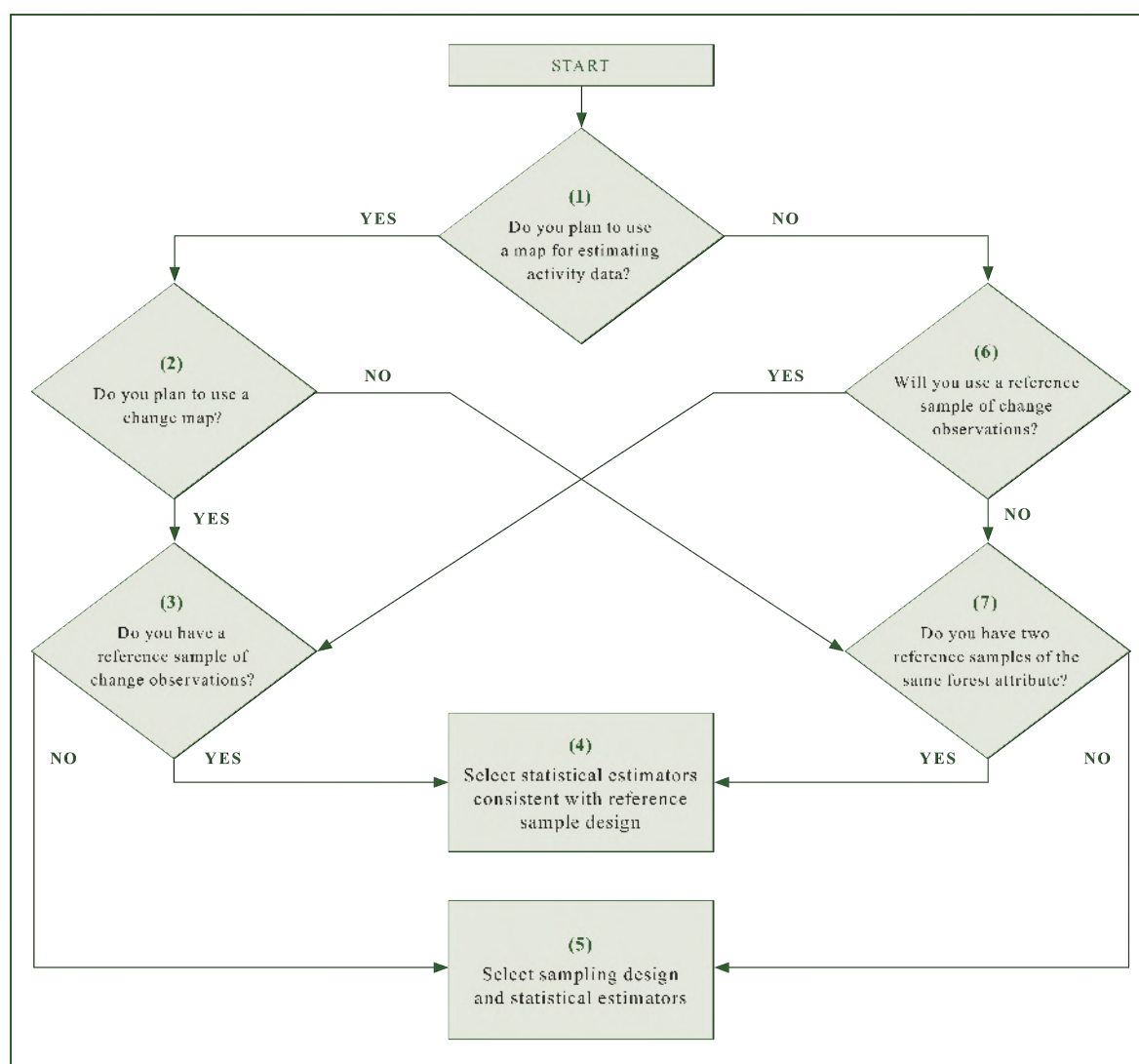
Considerations at the decision points in the tree are as follows:

Decision Point 1: Do you plan to use a map for estimating activity data?

> Although much of the literature on estimating activity data assumes that one or more maps will be used, there is no statistical requirement for doing so. Statistically rigorous and credible estimates can be obtained using only reference data[144]. The primary advantages of using maps are (i) that spatially explicit analyses are possible and (ii) that when used with reference data and appropriate statistical estimators, the precision of estimates may be substantially increased, thereby complying with the IPCC good practice guidance that "uncertainties are reduced as far as practicable" (IPCC, 2003; preface) Furthermore decision 4/CP.15 requires Parties to establish NFMS that provide estimates that are transparent, consistent, as far as possible accurate, and that reduce uncertainties, taking into account national capabilities and capacities. An underlying assumption in Figure 12.

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[144] As noted in the glossary, reference data are generally collected according to probabilistic sampling design. This means that they can be used alone to produce estimates associated with REDD+ activities, or they can be used in combination with remotely-sensed mapping data to correct for classification bias, and this approach may be most resource-efficient.

Guidance on choosing inference framework for estimation of activity data is that if a map can be acquired, then it will be used.

Decision Point 2: Do you plan to use a change map?

Because by definition activity data pertain to change, maps that enhance the estimation of activity data typically relate to change, although the exact manner in which they do so can vary. Change maps often depict change in land cover in the form of discrete map categories but may also depict proportions of attributes assigned to change categories such as continuous classification schemes that represent proportions of pixel area covered by specific land cover types. For decision advice, an assumption is that a change map will be used (i.e. answering "yes" to Decision Point 2) under two conditions: (1) a change map can be acquired, preferably by comparing images produced on a consistent basis from data gathered on two dates, or else by comparing two compatible maps for two dates, and (2) reference change data in the form of observations of the same locations for dates comparable to the change interval can be acquired.

Decision Point 3: Do you have a reference sample of change observations?

The primary issue is whether a reference sample of change observations obtained using a probability sampling design is already available or if it must be acquired.

Decision Point 4: Select statistical estimators consistent with reference sample design.

In this case, a sample is available and the selection of a statistical estimator and inferential approach must correspond to the sampling design used for selecting the reference sample. For example, if the reference sample was acquired using an STR sampling design, then STR estimators must be used. At this point (and at points 3 and 7), it is assumed that the sample size is considered appropriate to accommodate the guiding principles of IPCC."

Decision Point 5: Select sampling design and statistical estimators.

The selection of a sampling design and statistical estimator relies to a large extent on the nature of the map and the reference data. If the change map consists of forest/non-forest change/no change predictions, then a general recommendation is to use the map classes as strata and either SRS or SYS designs within strata (Olofsson et al., 2014). The primary advantage of STR sampling is that the precision of within-strata estimates (equivalent to activity data class estimates) can be controlled. In particular, for small or rare activity data classes, the number of observations obtained from overall SRS or SYS sampling can be too small to satisfy precision requirements[145]. However, if the reference data are acquired using an SRS design or an NFI-based SYS design, then PSTR estimators may produce considerably greater precision than SRS estimators. In general, to minimize the standard error of the activity data estimate, a stratified estimator is recommended if the map identified in Decision Point 2 depicts change in the form of discrete map categories whereas a model-assisted GREG estimator is recommended if the map depicts change in the form of proportions of map categories (Stehman, 2013; McRoberts et al., 2016).

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[145] Good practice is defined by IPCC as applying to inventories that contain *neither over- nor under-estimates so far as can be judged, and in which uncertainties are reduced as far as is practicable*. Although there is no pre-defined level of precision, this definition aims to maximize precision without introducing bias, given the level of resources reasonably available for GHGI development.

Decision Point 6: Will you use a reference sample of change observations?

The assumption underlying this and the succeeding decision points is that maps will not be used for estimating activity data. The substantive consequences are that opportunities for increasing the precision of the activity data estimates are not available and that spatial depictions of activity class locations cannot be constructed. For this decision point, the essential issue is whether reference change observations can be acquired; for these analyses, reference change observations consist of differences in observations of forest attributes acquired at the same locations for the two relevant dates. If such reference observations can be acquired, the assumption is that the reference sample of change observations will be used, primarily because the corresponding analyses are less statistically complex and less computationally intensive. If reference change observations cannot be acquired, such as when reference data are acquired from temporary NFI sample plots, separate analyses are required.

Decision Point 7: Do you have two reference samples of the same forest attribute?

The decision point assumes that at least one of the two conditions specified for Decision Point 2) is not satisfied, and therefore that it will not be feasible to use a change map for estimation of activity data. For example, acquisition of two forest attribute maps may be possible, but for some reason the maps cannot be compared to produce a change map. Additionally, acquisition of reference observations may be possible, but for some reason they cannot be acquired for the same spatial locations, perhaps because the reference data are acquired from an NFI that uses temporary ground plot locations. Three scenarios are possible: (a) both reference samples have been previously acquired, (b) one reference sample has been acquired previously and a second is yet to be acquired, and (c) both reference samples are yet to be acquired. For the first and second scenarios, the statistical estimators must be selected to be compatible with the sampling designs used to acquire the existing reference sample or samples. For the second and third scenarios, the assumption that reference change observations cannot be acquired precludes acquiring the two samples at the same locations. For these two scenarios, the combination of sampling design and statistical estimator for samples yet to be acquired can be either the same as, or differ from, a previously acquired sample, or from the other sample yet to be acquired.

Two examples presented in Box 24: A stratified approach to accuracy assessment and area estimation and Box 25: A model-assisted approach to accuracy assessment and area estimation illustrate methods for estimation of activity areas, one based on a stratification approach (Cochran, 1977; Olofsson et al., 2013, Olofsson et al 2014) for a map with categorical predictions, and the other based on a model-assisted approach (Särndal et al., 1992; Sannier et al., 2014) for a map with continuous predictions. These examples cover cases that are likely to be encountered in practice and illustrate how to generate unbiased estimates of activity areas with confidence intervals, thus satisfying the IPCC good practice criteria in Penman et al. (2003). As explained in Decision Point 5, the stratified approach illustrated in Example 1 is particularly useful when the strata correspond to activities. The model-assisted approach in Example 2 is more useful when the mapped response variable is continuous and when the relationship between reference data and map data used as auxiliary information can be exploited to increase precision.

An important distinction between the approaches illustrated in the two examples concerns the use of the map data. In the first example, the pixel-level map data are in the form of allocation to discrete classes and are used only to construct strata, to calculate stratum weights, and to reduce the variance of the area estimate relative to the variance of the estimate based only on the reference observations. Of importance, with the stratified estimator for the first example, the within-stratum estimates are based entirely on the reference observations. In the second example, the map data are used as a continuous, segment-

level, auxiliary variable. The model-assisted estimator facilitates greater exploitation of the relationship between the segment-level reference proportion of area and the segment-level map proportion of area. Consequently the model-assisted estimator requires compensation for the effects of segment-level model prediction error, but it also exerts a greater influence on the final estimates via a greater reduction in the variance error of the area estimate.

Box 24: A stratified approach to accuracy assessment and area estimation

Data and sampling design

A 30-m x 30-m Landsat-based change map for 2000 to 2010 consisted of two change classes and two non-change classes: (1) deforestation with area of 18,000 ha, (2) forest gain with area of 13,500 ha, (3) stable forest with area of 288,000 ha, and (4) stable non-forest with area of 580,500 ha. Because we have a change map and we intend to use it, the answer is "Yes" to Decision Points 1 and 2. A sample of reference observations did not exist and needed to be collected, so the answer is "No" at Decision Point 3.

For Decision Point 5, because the areas of the map change classes are small, together comprising only 3.5% of the total area, a STR design with the four map classes as strata was selected for acquiring the reference sample to be used for accuracy assessment. Because the map depicts change in the form of discrete map categories with the strata corresponding to activities, stratified estimation is suitable, with strata taking account of likely drivers of change. The sample size must be large enough to yield sufficiently precise estimates of the areas of classes but small enough to be manageable. A sample size of 640 pixels was distributed randomly with 75 pixels to each of the two change classes, 165 pixels to the stable forest class, and 325 pixels to the stable non-forest class following the recommendations in Olofsson et al. (2014).

Estimation

The Landsat pixels randomly selected for the sample reference data were subject to high quality manual classifications. The same underlying Landsat data were used to produce both the map and reference classifications, with the assumption based on three independent assessments that the reference classifications were of greater quality than the map classifications. An error matrix was constructed based on a pixel-by-pixel comparison of the map and reference classifications for the accuracy assessment sample (see Matrix 1), which uses the numerical data provided in the two previous paragraphs.

Matrix 1: Error matrix of sample counts

	Strata	Reference				Total	$A_{m,h}$ [ha]	w_h
		Deforestation	Forest gain	Stable forest	Stable non-forest			
Map	Deforestation	66	0	5	4	75	18,000	0.02
	Forest gain	0	55	8	12	75	13,500	0.015
	Stable forest	1	0	153	11	165	288,000	0.32
	Stable non-forest	2	1	9	313	325	580,500	0.645
	Total	69	56	175	340	640	900,000	1

The cell entries of the error matrix are all based on the reference sample. The sample-based estimator (statistical formula) for the area proportion, p_{hj}, is denoted as $\hat{p}_{hj}$, where h denotes the row and j denotes the column in the error matrix. The specific form of the estimator depends on the sampling design. For equal probability sampling designs, including SRS and SYS designs, and STR designs for which the strata correspond to the map classes, as is the case for this example,

Equation 14

$$\hat{p}_{hj} = w_h \frac{n_{hj}}{n_{h\cdot}}$$

where w_h is the proportion of the total area in s stratum (map class) h, (see the final column in Matrix 1) and n_h is n_{hj} summed over j.

Accordingly, the error matrix may be expressed in terms of estimated area proportions, $\hat{p}_{hj}$ (see Matrix 2), rather than in terms of sample counts, n_{hj} (see Matrix 1).

Matrix 2: Error matrix of estimated area proportions

			Reference				
	Strata	Deforestation	Forest gain	Stable forest	Stable non-forest	Total (w_h)	$A_{m,h}$ [ha]
Map	Deforestation	0.0176	0	0.0013	0.0011	0.020	18,000
	Forest gain	0	0.0110	0.0016	0.0024	0.015	13,500
	Stable forest	0.0019	0	0.2967	0.0213	0.320	288,000
	Stable non-forest	0.0040	0.0020	0.0179	0.6212	0.645	580,500
	Total	0.0235	0.0130	0.3175	0.6460	1	900,000

Once $\hat{p}_{hj}$ is estimated for each element of the error matrix; accuracies, activity areas, and standard errors of estimated areas can be estimated. User's accuracy, $\hat{U}_h = \frac{\hat{p}_{hh}}{\hat{p}_{h\cdot}}$, producer's accuracy, $\hat{P}_j = \frac{\hat{p}_{jj}}{\hat{p}_{\cdot j}}$, and overall accuracy, $\hat{O} = \sum_{h=1}^{H} \hat{p}_{hh}$, where H denotes the number of strata (map classes), are all estimated area proportions.

For this example, the estimate of user's accuracy is *0.88* for deforestation, *0.73* for forest gain, *0.93* for stable forest, and *0.96* for stable non-forest. The estimate of producer's accuracy is *0.75* for deforestation, *0.85* for forest gain, *0.93* for stable forest, and *0.96* for stable non-forest. The estimated overall accuracy is *0.95*. Note that accuracy measures cannot be estimated using the sample counts in Matrix 1 because the sample is stratified.

The estimated area proportions in Matrix 2 are then used to estimate the area of each reference class. The row totals of the error matrix in Matrix 3 are the map class area proportions (w_h) while the column totals are the estimated reference class area proportions.

Using the notation of Equation 6, and adding the subscript j to indicate reference class j,

Equation 15

$$\hat{\mu}_{hj} = \frac{1}{n_{h\cdot}} \sum_{i=1}^{n_{h\cdot}} y_{hji}$$

but because

Equation 16

$$y_{hji} = \begin{cases} 1 & if \ h = j \\ 0 & if \ h \neq j \end{cases}$$

Equation 15 can be expressed as,

Equation 17

$$\hat{\mu}_{hj} = \frac{n_{hj}}{n_{h\cdot}}$$

so that from Equation 7

Equation 18

$$\hat{\mu}_j = \sum_{h=1}^{H} w_h \cdot \hat{\mu}_{hj} = \sum_{h=1}^{H} w_h \cdot \frac{n_{hj}}{n_{h\cdot}} = \sum_{h=1}^{H} \hat{p}_{hj}$$

The area for reference class j is estimated as the product of $\hat{\mu}_j$ and the total area, A_{tot}. For example, the estimated area of deforestation the reference data is $\hat{A}_1 = p_1 \times A_{tot} = 0.235 \times 9000,000 = 21,158 ha$.

Thus, the mapped area of deforestation $(A_{m,1})$ 18,000 ha is an underestimate by 3,158 ha.

The next step is to estimate a confidence interval for the estimated area of each class. Using the notation of Equation 10 and again adding the subscript to denote reference class j,

$$\hat{\sigma}^2_{hj} = \frac{1}{n_{h\cdot} - 1} \sum_{i=1}^{n_{h\cdot}} \left(y_{hij} - \hat{\mu}_{hj} \right)^2$$

Noting from Equation 16 that $y_{hji}=0$ or $y_{hji}=1$, Equation 19 can be expressed as,

$$\hat{\sigma}^2_{hj} = \frac{1}{n_{h\cdot} - 1} \sum_{i=1}^{n_{h\cdot}} \hat{\mu}_{hj} \cdot \left(1 - \hat{\mu}_{hj} \right)$$

so that from Equation 8

$$V\hat{a}r\left(\hat{\mu}_j\right) = \sum_{h=1}^{H} w_h^2 \frac{\hat{\sigma}^2_h}{n_h} = \sum_{h=1}^{H} w_h^2 \cdot \frac{\hat{\mu}_{hj} \cdot \left(1 - \hat{\mu}_{hj}\right)}{n_{h\cdot} - 1} = \sum_{h=1}^{H} \frac{w_h \cdot \hat{p}_{hj} - \hat{p}_{hj}^2}{n_{h\cdot} - 1}$$

and standard error,

$$SE\left(\hat{\mu}_j\right) = \sqrt{V\hat{a}r\left(\hat{\mu}_j\right)}$$

From Equation 22, so that the standard error for the estimated area of forest loss is

$$SE\left(\hat{A}_1\right) = SE\left(\hat{\mu}_1\right) \, x \, A_{tot} = 0.0035 \times 900,000 \; ha = 3,142 \; ha.$$

A 95% confidence interval of the estimated area of forest loss is $\pm 1.96 \times 3,142 = \pm 6,158 \; ha$. Estimates and confidence intervals for all classes are shown in Matrix 3.

Matrix 3: Area estimates, standard errors and upper and lower 95% confidence interval limits.

Strata (j)	$\hat{\mu}_j$ [proportion]	$SE\left(\hat{\mu}_j\right)$ [proportion]	$\hat{\mu}_j$ [ha]	95% confidence interval	
				Lower [ha]	Upper [ha]
Deforestation	0.0235	0.0035	21,158	15,000	27,315
Forest gain	0.0130	0.0021	11,686	7,930	15,442
Stable forest	0.3175	0.0088	285,770	270,260	301,280
Stable non-forest	0.6460	0.0092	581,386	565,104	597,668

The stratified estimators presented in this section can also be applied if the sampling design is SRS or SYS where the map is used to define the strata (as identified above, this approach is sometimes referred to as "post-stratification" to distinguish the use of the strata for estimation from use of strata in the implementation of the sampling design)[146].

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[146] A software tool for these calculations available as well as a step-by-step explanation on how to perform an accuracy assessment resulting in an adjusted area estimate with a confidence interval.

Box 25: A model-assisted approach to accuracy assessment and area estimation

Data and sampling design

In Example 2, a 100,000-km^2 region of a tropical country was divided into 20-km x 20-km blocks with each block subdivided into 2-km x 2-km segments. A 30-m x 30-m, forest/non-forest classification was constructed for the entire region for each of 1990, 2000, and 2010 using Landsat imagery and an unsupervised classification algorithm. For each time interval, the map data for the ith segment consisted of the proportion of pixels, $\hat{y}_i$, whose classifications changed from forest to non-forest. Reference data were acquired for each year by randomly selecting one segment within each block and visually interpreting each pixel within the segment as forest or non-forest using independent Landsat data, aerial photography, and other spatial data. Although both the map and reference data were based on Landsat imagery, the reference data were considered of greater quality because of the use by skilled interpreters with access to additional information. The sample of segments was denoted S, and for each time interval, the reference data for the ith segment consisted of the proportion of pixels, y_i, whose visual interpretations changed from forest to non-forest. The Decision Points are the same as in Example 1, but because the map shows change in the form of proportions of map categories (which vary continuously), a model-assisted generalized regression (GREG) estimator is more suitable than the stratified estimator used in Example 1. For a general description of GREG estimators see section Section 5.1.5.

Estimation

For each time interval, consistent with the notation used for Equation 12 and Equation 13 above, the map-based estimate of proportion deforestation area was,

<div align="right">**Equation 23**</div>

$$\hat{\mu}_{map} = \frac{1}{N} \sum_{i=1}^{N} \hat{y}_i$$

where N = 25,000 was the total number of segments in the study area. However, the map estimates are subject to classification errors which introduce bias into the estimation procedure. An adjustment term to compensate for estimated bias is,

<div align="right">**Equation 24**</div>

$$\hat{Bias}\left(\hat{\mu}_{map}\right) = \frac{1}{n} \sum_{i=1}^{n} \left(\hat{y}_i - y_i\right)$$

where n = 250 is the number of segments in the sample. The adjusted (GREG) estimate is the map estimate with the adjustment term subtracted,

<div align="right">**Equation 25**</div>

$$\hat{\mu}_{GREG} = \hat{\mu}_{map} - \hat{Bias}\left(\hat{\mu}_{map}\right)$$

$$= \frac{1}{N} \sum_{i=1}^{N} \hat{y}_i - \frac{1}{n} \sum_{i=1}^{n} (\hat{y}_i - y_i)$$

The standard error (SE) of $\hat{\mu}_{GREG}$ is,

Equation 26

$$SE(\hat{\mu}_{GREG}) = \sqrt{V\hat{a}r(\hat{\mu}_{GREG})} = \sqrt{\frac{1}{n \cdot (n-1)} \sum_{i=1}^{n} (\varepsilon_i - \bar{\varepsilon})^2}$$

where $\varepsilon_i = (\hat{y}_i - y_i)$ and $\bar{\varepsilon} = \frac{1}{n} \sum_{i=1}^{n} \varepsilon_i$

This estimator is based on an assumption of a SRS design. For a SYS design, the variances and standard errors may be over-estimated, yielding conservative estimates of confidence intervals. Estimates of deforestation area for each time interval are shown in Matrix 25.1 In the statistical literature, these estimators are characterized as the model-assisted GREG estimators even though prediction techniques other than regression may be used and the model may be implicit (Särndal et al., 1992; section 6.5).

Matrix 1: Area estimates, standard errors and upper and lower 95% confidence interval limits.

Interval	$\hat{\mu}_{GREG}$ [proportion]	$SE(\hat{\mu}_{GREG})$ [proportion]	$\hat{\mu}_{GREG}$ [ha]	95% confidence interval Lower [ha]	Upper [ha]
1990-2000	0.0033	0.0012	33,000	9,480	56,520
2000-2010	0.0011	0.0012	11,000	0*	34,520
1990-2010	0.0044	0.0016	44,000	12,640	75,360

*Because the lower limit was negative, it was reset to 0.

5.2 Emissions/removals factors

This section is mainly about emissions and removals factors used in REDD+ estimation. In some cases modelling is involved, to establish allometrics, or more complex Tier 3 models. The section also refers to the model parameters relevant in these cases which are used for emissions and removals estimation but are not part of the activity data estimation. These parameters can be regarded as emission or removals factors in a general sense, although the equations in which they are used may be more complicated than a simple activity data x emission factor product.

5.2.1 Above- and belowground biomass

Emission and removals relating to REDD+ activities result from changes in carbon pools. In most circumstances above- and belowground biomass pools are likely to be key carbon pools and methods are required to estimate changes in biomass carbon stocks.

The methods for calculating emissions and removals from each REDD+ activity described in Chapter 3, Section 3.1 require emission/removal factors related to estimates of biomass carbon density and change in carbon density within reported forest strata. For example, the gain-loss methods described in Chapter 3, Section 3.1 requires the following:

▸ biomass carbon densities in primary forest, modified natural forest, and planted forest sub-stratified as required by forest type, and management regime or likelihood of disturbance[147]

▸ annual rates of change in biomass carbon density in modified natural forest sub-stratified as required by forest type and management regime or likelihood of disturbance

▸ long-run average biomass carbon density and corresponding rates of change in planted forest sub-stratified as required by forest type and management regime or likelihood of disturbance.

5.2.1.1 Use of forest inventory plot data and allometric models for biomass estimation

Biomass carbon density is generally estimated from forest inventory (plot measurements) (Chapter 4, Section 4.2.1) by using allometric models which relate biomass to surrogate measurements such as trunk diameter and height. Allometric models are established using destructive sampling which can be expensive. Some appropriate allometric models may already exist, and supplementary studies can fill gaps for other major species or forest types and environmental zones identified. Growth and yield trials, forest experiments and other quality data sources held by universities or other research agencies may be useful for the development or verification of models. The spatial, environmental or other limits of such models will need to be determined to ensure they are not applied outside their domain of relevance, as this may introduce bias. Any gaps, especially in the root-to-shoot or below-ground allometrics could be filled through targeted new studies.

Allometric models should preferably estimate above- and below-ground biomass, and be developed for relevant tree species and circumstances. The application of species specific allometric models requires knowledge of species composition within the identified forest strata. Different allometric models may be needed for each stratum, therefore the availability of appropriate allometric models can be a practical constraint on the number of forest strata used, and new allometric models may need to be developed. Some useful biomass information may already be available through an NFI, and the agency responsible for the NFI should be consulted via the NFMS about the relationship between NFI data, the proposed stratification for estimating REDD+ activities, and the availability of suitable allometric models. This should be done before new field work is done or further stratification is decided. Advice on the design of NFIs and the challenges of measuring plots in tropical rainforests is provided in Chapter 4, Section 4.2.1.

FAO and CIRAD have published a manual on how to develop allometric models and a database of existing models with information on the circumstances under which they apply and information on associated uncertainties. For native forests, which may contain many different species, application of

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[147] Chapter 2, Section 2.3.2

species-specific allometric models may be impractical, in which case non-species-specific, regionally relevant allometric models can be used (Chave et al., 2004). Generic equations are based on large numbers of trees sampled across landscapes, and tend to be more reliable than locally developed equations if these are based on only a small number of trees (Chave et al., 2005; Chave et al., 2014; Paul et al., 2016).

The suitability of existing allometric models should be evaluated before they are applied in new circumstances. This requires consideration of how many trees were destructively sampled to develop the model, how well the sampled trees used to develop the model match the diameter distribution in the population of trees to which it is applied, and how well the model can estimate the biomass of an independent set of sample trees (Roxburgh et al., 2015; Perez-Cruzado et al., 2015). For model validation, a minimum of 10 trees need to be sampled in homogenous monoculture forest and many more (perhaps 50) in diverse natural forests. In all cases, allometric models should not be applied to trees outside the diameter range used to develop the model because this can introduce serious errors and bias (see Appendix F).Where allometric models that only estimate above-ground biomass are available below-ground biomass can be estimated using root-to-shoot ratios, default values are available from IPCC[148], although this approach will increase uncertainties.

Biomass densities should be multiplied by mass of carbon per mass of biomass to convert to carbon densities. The default ratio in the GPG2003 is 0.5[149]. More specific figures for tree components and forest domains are given by IPCC[150]. Box 26: Considerations when establishing and applying allometric models provides some further considerations relating to the development and use of allometric models.

Estimating annual net change in biomass carbon stocks can be achieved by repeated plot measurements or from estimates of annual growth and carbon loss due to wood removals (including firewood) and / or other disturbances such as fire. Transfer of biomass to dead organic matter is based on estimates of annual biomass carbon lost due to mortality and carbon transfer to slash if the forest has been harvested.

Tier 2 and 3 approaches for biomass carbon stock change estimation allows for a variety of methods, and uses country-specific data to calculate the above-ground biomass growth and losses generally from repeated NFI data and/or empirical growth models. Implementation may differ from one country to another, due to differences in inventory methods, forest conditions and available activity data.

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[148] Chapter 4; Table 4.4 of 2006GL

[149]

[150] Chapter 4; Table 4.3 of 2006GL.

Box 26: Considerations when establishing and applying allometric models

When establishing allometric models, the range of tree sizes sampled should cover that encountered in the forest of interest. Failure to sample adequately large trees (many trees may exceed 100 cm in diameter in tropical forests; Henry et al., 2010) will result in very uncertain biomass estimates[151]. Generally tree diameters should be measured at least 130 cm above the ground and below the first branching point.

In the application of allometric models countries should select models that have been developed consistently with established and validated practice and that best represent their forest types, measured stem diameters and heights. In both cases (establishment and application) all methods and choices should be well documented and justified.

5.2.1.2   Use of remote sensing data in biomass estimation

Although optical imagery does not directly estimate biomass, spectral attributes are related to biomass and can be used in conjunction with field data and models to provide spatially explicit estimates of biomass and other vegetation attributes. One limitation of both Landsat and MODIS is that the passive optical signals saturate (no longer respond to further increase) at moderate-to-high levels of leaf area, so that these sensors cannot differentiate between ecosystems with moderate-to-high levels of biomass. Landsat and MODIS are also unable to detect early regrowth of secondary vegetation, and do not reveal small disturbances such as removal of individual trees, which may be important for monitoring forest degradation.

The detection limitations of Landsat and MODIS can be overcome by high-resolution optical sensors, aerial photographs and active sensors such as LIDAR or SAR. Application of these remote-sensing instruments is currently limited to smaller areas because of the high volume of data and cost.

Mitchard (2015) and Saatchi (2015) provide an analysis of the strengths and limitations of remote-sensing approaches for estimating tropical forest biomass across differing biomass densities and spatial scales. Different approaches are proposed depending on the scale of application (ranging from airborne LIDAR for finer scales of the order of tens of thousands of hectares, to use of a calibrated land cover map for scales of 1 million hectares or more) and the level of precision required, based on policy needs and cost. In all cases reliable ground observations are required to calibrate the remotely sensed data and advice is given on how to obtain such data.

Appendix G provides a brief review of the potential for estimation of biomass by remote sensing.

5.2.2   Dead wood and litter pools

Tables 3.2.1 and Table 3.2.2 in GPG2003[152] provide some default data on the deadwood and litter pools. For the purposes of REDD+ estimation, emissions and removals associated with REDD+ activities, carbon stock changes within these pools need to be obtained by sampling, ideally from the same

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[151] Chave, et al. (2004) found that for tropical rainforest the coefficient of variation associated with the allometric model was ~ 20% when 20 trees were sampled to construct it, but that this declined to 10% when the sample size was ~50 trees.

[152] See also Table 2.2 of volume 4, chapter 2 of 2006GL

sampling sites established for biomass estimation. If methods for estimating these pools are not already established, e.g. via a NFI, countries could apply the methods set out by the UNFCCC for use with afforestation and reforestation projects under the Clean Development Mechanism[153].Tier 3 methods utilise mass-balance models that encompass all carbon pools including the deadwood and litter pools as well as the movements between all pools (Box 11: Mass Balance Approaches). In such cases countries would have models calibrated to develop estimates for the deadwood and litter pools consistent with their identified forest strata.

5.2.3 Soil organic carbon

IPCC provides Tier 1 methods for estimating CO_2 emissions and removals on mineral soils associated with the transitions from

▸ forest to non-forest land uses that sum to deforestation,

▸ other land uses to forest.

The Tier 1 method assumes that mineral soil carbon stock density on land that has been forest for at least 20 years will be equal to the mineral soil carbon stock density under native vegetation for the relevant climate and ecosystem type and that where there are transitions to or from another land use, the mineral soil carbon stock density on the other land use in question will be that value times a relative carbon stock change factor depending on the land use, the level of management and the climate. Following transition between land uses carbon is emitted or removed over a 20 year transition period at which time the new carbon value is assumed to be achieved.

At Tier 1 IPCC assumes that mineral soil carbon stocks do not change for land remaining in forest land use. For drained organic soils IPCC provides emission/removal factors which depend on climate and ecosystem and will produce emissions so long as the land is drained and organic carbon remains. The relevant tables in the IPCC guidance are summarised in Table 15: IPCC emissions and removal factors associated with soil carbon stocks and Table 16: IPCC emission and removal factors associated with non-carbon dioxide emissions from the soil.

Where soil-related emissions are key (Chapter 2, Section 2.2.3) countries should aim to apply higher Tier methods. Developing estimates of temporal change in soil carbon stocks using repeated field sampling is challenging. This is because soil carbon stocks are large and spatially variable so that it is almost impossible to detect changes which are usually small (generally only a few % of the total stock) unless intensive and expensive sampling is undertaken. Instead, for Tier 1 default reference carbon stocks (i.e. carbon stocks under native vegetation and default soil C change factors (multipliers capturing the effect of management practices and land uses) are applied. At Tier 2, the method is the same, but default values are replaced by country-specific values. Tier 3 methods employ detailed modelling of soil C dynamics, requiring detailed calibration and validation data and large and long-term investment for their development.

Whatever approach is used, soil maps are required in combination with soil carbon change factors or more complex models. Some maps may already be held by Agriculture and Forestry agencies, but their spatial resolution may need to be enhanced based on further soil survey before they can be applied to REDD+ activities. For many inaccessible tropical forest areas soil maps may not exist, or have poor spatial resolution. This is especially so for peat and other carbon-rich soils, which are important sources

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[153] EB67 report, Annex 23.

of carbon emissions due to biological oxidation or fire following forest disturbance. Barthelmes et al., (2015) provide valuable advice on how existing maps combined with remote sensing which can provide useful vegetation and topographic surrogates for soils, and new ground surveys can be effectively integrated to map organic soils under tropical forests at scales useful for management decision making.

At Tier 1, the IPCC 2013 Wetlands Supplement provides default emission/removal factors for non-CO_2 greenhouse gases associated with the processes shown in Table 16: IPCC emission and removal factors associated with non-carbon dioxide emissions from the soil below:

Under some conditions nitrous oxide (N_2O) can be released from soils. Emissions can be either direct (derived from local soil management processes) or indirect (resulting either from atmospheric deposition of N or inputs of N from leaching or run-off from elsewhere). Emissions of N_2O are increased following the addition of N fertilizers, or by any forest management practices that increase the availability of inorganic N in soils. IPCC[154] provides guidance on how to estimate emissions of N_2O from managed soils which is cross-referenced in the guidance in GPG2003 (see Table 21 below).

N_2O emissions would not usually represent a key category for forests unless lands have had heavy application of N fertilizer; this combined with the complexity of estimating emissions of N_2O means most countries will use Tier 1 approaches unless they have undertaken replicated field studies to demonstrate that the IPCC default factors are inappropriate for their circumstances.

The activity data needed to implement the Tier 1 approach are the quantity of N fertilizer used and other organic amendments added, and an estimate of the area of land to which the management activity has been applied. The IPCC provides Tier 1 emissions factors for both direct and indirect emissions from the identified area of management (i.e. activity data).

Table 15: IPCC emissions and removal factors associated with soil carbon stocks

Parameter	2003 Good Practice Guidance	2006 Guidelines	2013 Wetlands Supplement
Mineral Soil Organic Carbon reference carbon stocks	Table 3.2.4 Table 3.3.3 Table 3.4.4	Table 2.3	Table 5.2
Relative carbon stock change factors	Tables 3.3.3 Table 3.4.5	Table 5.5 Table 5.10 Table 6.2	Table 5.3
Drained and rewetted organic soil emission/removal factors	Table 3.3.5 Table 3.4.6	Table 4.6, Table 5.6 Table 6.3	Table 2.1 Table 2.2(a) Table 3.1 (b) Table 3.2(a)

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[154] See GPG2000, Chapter 4, sections 4.7 and 4.8. The corresponding section in the 2006GL can be found in and Vol 4, Chapter 11.

Parameter	2003 Good Practice Guidance	2006 Guidelines	2013 Wetlands Supplement
Change due to fires	--	--	Table 2.6 Table 2.7
Soil carbon stocks in mangroves	--	--	Table 4.11 (c)

Notes: a) emission/removal factors in Table 2.2 of the wetlands supplement are for estimating emissions of CO_2 from waterborne carbon arising from drained and rewetted organic soils. b) Removals and emissions factors in Table 3.1 of the wetlands supplement are for rewetted organic soils. c) This table provides undisturbed soil carbon densities. Carbon in extracted soil is assumed by default to be oxidized in the year of extraction.

Table 16: IPCC emission and removal factors associated with non-carbon dioxide emissions from the soil

Parameter	Location in 2013 Wetlands Supplement
CH_4 emissions and removals from drained and rewetted inland organic soils	Table 2.3 Table 2.4 Table 3.3
N_2O emissions and removals from drained inland organic soils	Table 2.5
CO and CH_4 emissions and removals from fires on drained inland organic soils	Table 2.6 Table 2.7
CH_4 and N_2O from mangroves	Table 4.14 Table 4.15
N_2O from aquaculture in mangroves	Table 4.15
CH_4 from rewettted inland wetland mineral soils	Table 5.4

Table 17: IPCC emission and removal factors associated with direct and indirect nitrous oxide emissions from soil

Parameter	2003 Good Practice Guidance	2006 Guidelines
Emission/removal factors related to direct N_2O emissions from managed soils	1.25 % of applied N	Table 11.1
Emission/removal factors related to indirect N_2O emissions from managed soils		Table 11.3

5.2.4 Emissions from prescribed fires and wildfires

Biomass burning occurs in many types of land uses causing emissions of CO_2, CH_4, N_2O, CO, and NO_x. The IPCC provides Tier 1 methods for estimating emissions from two general types of biomass burning: burning within managed forests (i.e. forest land remaining forest land) and burning in the course of land use conversion (i.e. Land converted to Forest land; Land converted to Cropland; Land converted to Grassland).

IPCC methods group fires into two categories: prescribed (or controlled) fires and wildfires. Prescribed fires include: (i) land clearing fires in the course of forest conversion, (ii) slash-and-burn agriculture, (iii) post-logging burning of harvest residues (slash); and (iv) low-intensity prescribed fire for fuel load management. Wildfires are typically more variable (i.e. in temperature and thoroughness of biomass combustion) than prescribed fires making estimation of emissions from these events more difficult.

In accordance with IPCC[155], when managed land is burned, emissions resulting from both prescribed fires and wildfires should be reported so that carbon losses and non-CO_2 GHG emissions on managed lands are taken into consideration.[156]

At Tier 1 IPCC assumes that emissions from fire are the sum of the area burnt multiplied by the fuel available for combustion per unit area taking into consideration the fraction of available fuel combusted and the mass of each GHG emitted per unit of fuel combusted[157]. Emissions of each gas are estimated individually, and then are summed to give the total GHG emissions due to fire. The location of relevant IPCC Tier 1 factors are summarised in Table 18: IPCC emissions factors for prescribed fires and wildfires below.

Table 18: IPCC emissions factors for prescribed fires and wildfires

Parameter	2003 Good Practice Guidance	2006 Guidelines
Fuel burnt	Table 3.A.1.13 which tabulates the product of B (the available fuel, or biomass density on the land before combustion) and C (the combustion efficiency	
Available Fuel		Table 2.4
NonCO$_2$ emissions from C released	Table 3.A.1.15	Table 2.5
Combustion efficiency	Table 3A.1.12	Table 2.6
N/C ratio for the fuel burnt	0.01	0.01

Tier 2 or 3 is required where fire is a key category of GHG emissions. Countries applying Tier 2 are likely to have national data at disaggregated level on the mass of fuel available according to forest types and management systems. Tier 3 estimation requires spatial estimates of the mass of fuel available according to different forest types, regions and management systems. Tier 3 estimation methods may

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[155] Refer to GPG2003 section 3.2.1.4.2 and Volume 4, Chapter 4.2.1 and 4.2.4 of the 2006GL

[156] Fire impact in unmanaged forest lands should not be reported.

[157] Refer to chapter 3, section 3.2 of GPG2003, specifically Equation 3.2.20 for specific guidance on the use of this equation. The corresponding guidance is in volume 4, section 2.4 of the 2006GL

also be able to distinguish fires burning at different intensities, resulting in different amounts of fuel consumption. Fully integrated, mass-balance Tier 3 systems estimate emissions based on the ecosystem type, the biomass on the site at the time of the fire and the type (e.g., wildfire, prescribed burning) and intensity of the fire. These systems also estimate the subsequent recovery from fire (uptake of CO_2) and ongoing release from trees killed by the fire. These systems are particularly effective when maps of fire extent are available.

Tier 2 or 3 methods should avoid double counting of CO_2 emissions from fire in particular where carbon loss is derived from repeated field measurements (i.e. NFI) since estimates of change from ground measurements could include the carbon loss from fires.

5.2.5   National choices in emissions and removals factor estimation

The decision tree in Figure 13: Guidance on choosing inference framework for estimation of emissions and removals factors is intended to guide countries through the choices likely to arise in practice when considering the use of data to estimate biomass emissions and removals factors, taking account of the preceding discussion. The numbers in the decision point boxes refer to explanations following the tree. Non-biomass pools and other GHG are covered more generically in Section 5.2.4.

Figure 13: Guidance on choosing inference framework for estimation of emissions and removals factors
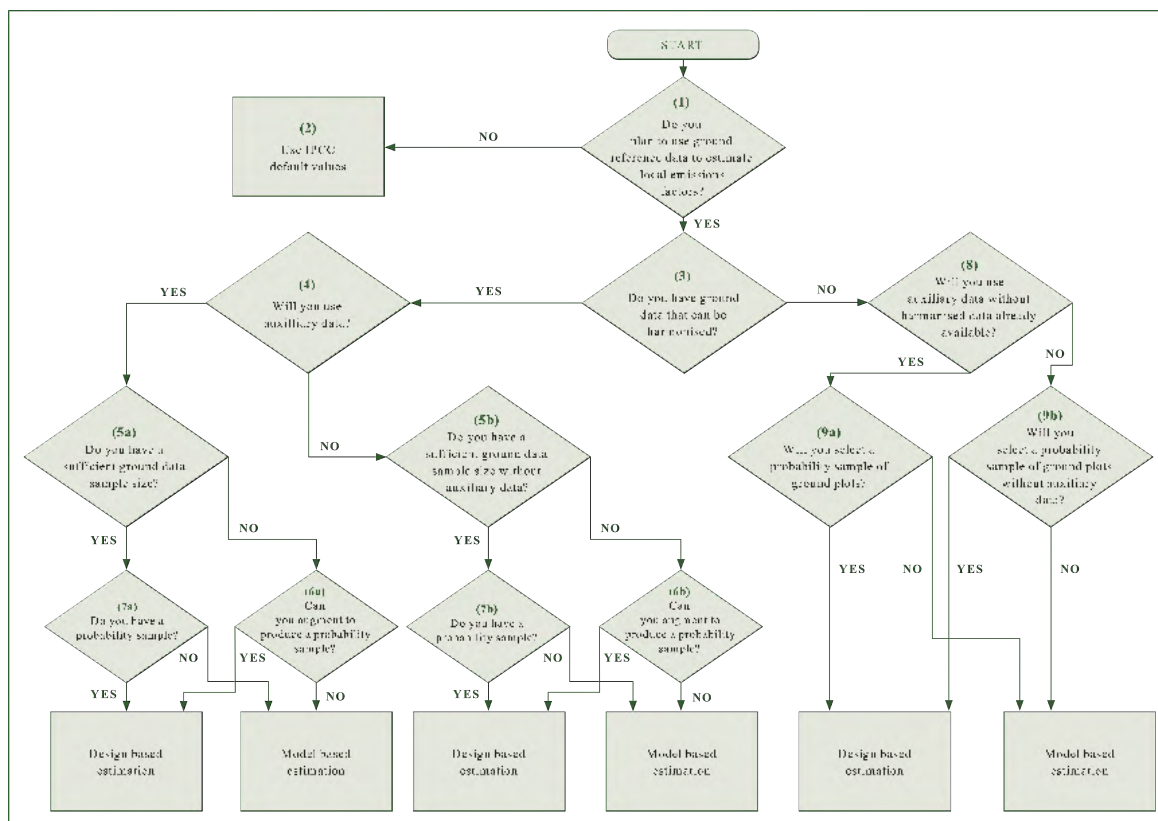
Considerations at the decision points in the tree are as follows:

Decision Points 1 and 2. Use ground reference data[158] to estimate emissions and removals factors

The answer to the question in decision point 1 will usually be YES because countries for which REDD+ activities are key, and/or for which significant amounts of ground-based data exist, will generally make use of the data for REDD+ estimation. If ground reference data are not to be used (answer NO at decision point 1 leading to decision point 2) countries can use IPCC default values in Tier 1 estimation. This should not be done for key categories or where adequate ground data are available. Countries may also want to consider the IPCC Emission Factor Database as a possible source of emission/removal factors. The database contains factors that have undergone an editorial review process though not the full IPCC review so they do not have the same status as defaults contained in the IPCC's methodological reports, and their use is a matter of scientific judgement by technical experts responsible for the estimates. Uncertainty ranges associated with the use of defaults should be taken from the IPCC guidance and guidelines.

Decision Point 3. Do you have data that can be harmonized?

Harmonization entails putting data on the same basis – for example by use of consistent measurement thresholds, consistent definitions, and common assumptions regarding species wood density or carbon conversion factors. The NFMS should check that this is the case with the collated data, leading to the response YES at this decision point. In the absence of ground data that can be harmonized (leading to the response NO) the NFMS should initiate the collection of the ground data needed.

Decision Point 4. Use auxiliary data?

Auxiliary data refers to the information used in stratification to increase sampling efficiency or as an input to models. Increased efficiency implies lower costs for given precision so in general, where available, auxiliary data should be used for stratification purposes. The answer to this question will generally be YES unless the forests in the country are so uniform as to render stratification unnecessary.

Decision Points 5a, 6a and 7a Decisions related to sample size in the presence of auxiliary data

The data sample size is sufficient if the confidence intervals associated with the emission/removal factors estimated for the strata defined using auxiliary data meet the specified precision criterion. If this is not already known to be the case (which would already lead to a YES at point 5a) then with a probability sample (which will lead to a YES at decision point 7a that immediately follows it can be determined in the first instance by reconnaissance calculations of the type described under sample size in the account of sampling in Appendix B. In the absence of a probability sample (leading to a NO at decision point 7a) then, Monte-Carlo or other uncertainty analysis being used with model-based inference will be needed. If the reconnaissance estimates or Monte Carlo analysis indicate a NO at point 5a then at 6a the sampling will need augmentation as described under supplementary sampling in Appendix B.

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[158] As noted in the glossary reference data are the best available assessment of conditions on the ground for a given location or spatial unit. Reference data can be used to estimate areas or carbon densities and associated standard errors based on sampling. Reference data are generally collected according to probabilistic sampling design.

Decision Point 5b.6b, 7b Decisions related to sample size in the absence of auxiliary data

Considerations apply as for decision points 5a, 6a and 7a except that in the absence of auxiliary data there will be no basis for stratification. Unless the forests in question are a statistically uniform population this will increase the amount of sampling needed to satisfy precision requirements, and hence increase sampling costs. If this is an issue the NFMS should consider obtaining the auxiliary data needed for stratification, so that the left hand branch can be executed following a YES at decision point 4.

Decision Point 8. Use auxiliary data without harmonized data already available?

Having answered NO at decision point 3 the assumption is that the NFMS will make arrangements to gather the data needed for estimating emissions/removals factors to satisfy precision requirements. On this side of the decision tree there is no need for consideration of augmentation of an existing dataset because the sampling is designed from the beginning. In most cases auxiliary data (collated by the NFMS) will be used for stratification because of the need to increase sampling efficiency and reduce costs, and therefore the answer at decision point 8 will be YES. If auxiliary data are not being used there will be no basis for stratification and the NO branch should be followed.

Decision Point 9a. Select probability sample of ground plots with auxiliary data?

In case of a probability sample (leading to the left-hand branch below 9a), the sample will need to be sufficient if the confidence intervals associated with the emission/removal factors estimated the strata defined using auxiliary data meets the specified precision criterion. This can be determined in the first instance by reconnaissance surveys of the type described under sample size in the account of sampling provided in Appendix B. The individuals to be sampled will depend on the purpose of the sampling as described in Appendix B under selecting which individuals to sample. If the sampling is in conjunction with model-based inference (leading to the right hand branch below 9a) the sampling will be used to establish model parameters and needs to be sufficient that the confidence interval for model outputs of interest (e.g. carbon densities) meets criteria set out by the NFMS for the policy purpose intended. The model sensitivity analysis and exploratory runs are the equivalent of reconnaissance surveys to establish what is needed.

Decision Point 9b. Select probability sample of ground plots without auxiliary data?

Considerations apply as for decision point 9a except that in the absence of auxiliary data there will be no basis for stratification. Unless the forest population in question is statistically relatively homogeneous with respect to the target variable(s) the amount of sampling needed to achieve target precision will increase, and hence increase sampling costs. If this is an issue the NFMS should consider obtaining the auxiliary data needed for stratification, so that the left hand branch can be executed following a YES at decision point 8.

Decision Point, final: design- or model-based inference?

As set out in the box above, design-based , inference is based on sample points distributed according to probabilistic rules across the forest landscape - whereas in the case of model-based inference the sampling is used to establish model parameters and need not follow the same probabilistic rules, though to be effective it should cover the range of forest types and circumstances likely to be encountered in practice. Model-based inference relies on correct model specification as the basis for valid inference and to minimize bias, rather than a probability sampling design. The advantages are that a model offers opportunities for incorporating scientific understanding e.g. on the relationship

between carbon pools, and this may increase predictive power. Model-based inference can also accommodate sample data that may not have been gathered according to a particular sampling design. The disadvantages are that there is no general agreement on what model to use, and the analysis of uncertainties is more complicated because sampling theory applied to models does not yield relatively simple formulae. For this reason Monte-Carlo analysis is often used to generate uncertainty estimates, though this relies on sufficient understanding of the correlations that may exist between different parameters.

5.2.6 Emission and removal factor uncertainties

Where default values are used, uncertainties for emission and removal factors and other parameters are available from GPG2003 (or 2006GL and the Wetlands Supplement), and for Tier 2 and 3 methods will be generated as part of the sampling process. When based on probabilistic sampling, the emissions/removals factors and their uncertainty can be calculated using two broad methods, depending on whether the emission or removal factor corresponds to the difference of carbon densities between strata, or to the change in carbon density of a given stratum over time. The focus of this section is on changes in biomass carbon, non-CO_2 emissions/removals can be calculated analogously if they have also been measured as part of the sampling program.

5.2.6.1 Method 1: Calculation of emissions/removals factors from spatially segregated strata

For the first method, two spatially segregated strata that differ in carbon density (A and B) can be independently sampled, with the mean emission/removal factor given by:

Equation 27

$$\hat{\mu}_{EF} = \hat{\mu}_B - \hat{\mu}_A$$

where $\hat{\mu}_A$ and $\hat{\mu}_B$ are the mean carbon densities for each stratum as calculated from the sample.

In this context stratum A could correspond to modified natural forest (MNF), and stratum B to primary forest (PF), with $\hat{\mu}_{EF}$ therefore corresponding to the term $[CB_{PF} - CB_{MNF}]$ in Equation 1 in Chapter 3, Section 3.1.2.

Because the sampling in each of the strata is independent, the uncertainty of $\hat{\mu}_{EF}$ can be calculated as

Equation 28

$$V\hat{a}r\left(\hat{\mu}_{EF}\right) = V\hat{a}r\left(\hat{\mu}_A\right) + V\hat{a}r\left(\hat{\mu}_B\right)$$

Where $V\hat{a}r\left(\hat{\mu}_i\right)$ is the variance of the estimate of the respective mean (see also Section 5.1.5.1, Equation 2).

Note that $\sqrt{V\hat{a}r\left(\hat{\mu}_i\right)}$ is often called the standard error, and when multiplied by the appropriate $t_{0.95}$ statistic (usually taken to be 1.96) gives the 95% confidence interval. Equation 28 corresponds to Rule

A of section 6.3 of GPG2000[159], which is cross-referenced in section 5.2.2.1 of GPG2003 - although Rule A is expressed in terms of 95% confidence intervals, rather than variance.

5.2.6.2 Method 2: Calculation of emissions/removals factors from change-over-time

For the second method, the same strata are monitored through time, and if change occurs (such as clearing or degradation) then an emissions/removals factor can be calculated from the observed change,

$$\hat{\mu}_{EF} = \hat{\mu}_{t_2} - \hat{\mu}_{t_1}$$

Where $\hat{\mu}_{t_1}$ and $\hat{\mu}_{t_2}$ correspond to the carbon density of the forest before and after the change, respectively.

The calculation of the uncertainty of the emission/removal factor in this case depends upon the sampling design, and in particular whether there were permanent plots that were surveyed at both t_1 and t_2. In the simple case when there were no permanent plots and the carbon density estimates were obtained from independent samples at t_1 and t_2, then the overall uncertainty can be calculated in an analogous way to Equation 28,

$$V\hat{a}r\left(\hat{\mu}_{EF}\right) = V\hat{a}r\left(\hat{\mu}_{t_2}\right) + V\hat{a}r\left(\hat{\mu}_{t_1}\right)$$

In contrast, if the plots were permanently located and if all of the sample plots measured at t_1 were re-measured at t_2, then the samples are correlated, and this correlation should be taken into account. In this case the uncertainty in $\hat{\mu}_{EF}$ is given by,

$$V\hat{a}r\left(\hat{\mu}_{EF}\right) = V\hat{a}r\left(\hat{\mu}_{t_2}\right) + V\hat{a}r\left(\hat{\mu}_{t_1}\right) - 2r\sqrt{V\hat{a}r\left(\hat{\mu}_{t_2}\right)}\sqrt{V\hat{a}r\left(\hat{\mu}_{t_1}\right)}$$

where r is the correlation in biomass density from t_1 to t_2 across the sample plots.

When biomass density is positively correlated between t_1 and t_2, then the final term of Equation 31 acts to reduce the overall variance, and thus to increase the precision. More generally, Equation 30 and Equation 31 can also be used to determine the uncertainty of any change in measured biomass between two time periods, such as in the analysis of general forest monitoring. In this case and in the absence of significant disturbance the correlation is likely to be high, and typically greater than 0.8 (Köhl et al., 2006) especially if t_1 and t_2 are relatively close together in time (< 10 years apart).

Equation 30 and Equation 31 represent two extreme cases where either all of the original plots were re-surveyed Equation 31), or none of the original plots were re-surveyed (Equation 30). The intermediate

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[159] Corresponding to volume 1, section 3.2.3.1 of 2006GL.

situation occurs when only a fraction of the plots are permanent, with some plots only measured at t_1, and some plots only measured at t_2. This can occur if e.g. some plots were lost or destroyed after t_1 but were replaced by other plots at t_2, or if there were difficulties with re-locating plots in the field. Ensuring a mixture of both permanent and temporary plots can also be built into the survey design to provide some insurance against the situation where, over time, permanent plots become non-representative, thus potentially introducing bias.

A sampling design with a mixture of temporary and permanent plots is known as sampling with replacement (Loetsch & Haller, 1964), with the calculation of the estimate of $V\hat{a}r(\hat{\mu}_{EF})$ being more complex than either of the extreme cases. Köhl et al., (2015) provide a more complete description of sampling with replacement in the context of REDD+, and also present the calculations required to estimate $V\hat{a}r(\hat{\mu}_{EF})$ for this situation. These calculations use linear regression to update the mean carbon density at t_1 based on information embedded within the t_2 survey results, and therefore the estimate for the mean change in carbon density no longer equals the simple difference given in Equation 21. If this is considered undesirable, then an alternative estimate for $V\hat{a}r(\hat{\mu}_{EF})$ under sampling with replacement (Päivinen & Yli-Kojola, 1989) can be used instead. The calculation is described in Box 27: Calculation of the uncertainty of emissions/removals factors under sampling with replacement.

Reducing uncertainties

Uncertainties in the estimation of emission/removal factors can be reduced by:

- increasing sampling density without further sub-stratification

- further sub-stratification to focus sampling on forest areas likely to be affected by REDD+ activities, after as well as before the transfers between strata or land use change has occurred.

  If further stratification is adopted then the estimates for $\hat{\mu}_{EF}$ and $V\hat{a}r(\hat{\mu}_{EF})$ may need to be calculated using the estimators appropriate for a stratified sampling design, as described under '*Stratified estimators*' in Section 5.1.5. No more than 6-8 strata are generally recommended (Cochran 1977, p134).

- retaining the same stratification and sampling density but using auxiliary information to verify the direction of change. For example in the case of degradation, if the direction of transfer was consistent with advancing forest fragmentation, then increased forest carbon density would be unlikely and the probability distribution of the degradation estimate should be considered truncated so as to eliminate the possibility of increases.

- Increasing the number of permanent sample plots, if using Method 2 to estimate the change in carbon density over time.

Other uncertainties

The calculation for the uncertainty of the emissions factor $V\hat{a}r(\hat{\mu}_{EF})$ given in Equation 28 and Equation 30 includes only error due to sampling, and although it is typically the most important source of error, there are a number of other error sources, such as measurement errors, errors associated with the use of allometric models used to predict tree biomass, or errors in expansion factors such as root:shoot ratios for estimating below-ground biomass. These additional errors can be considered independent from the sampling error, and thus the total error variance can estimated by adding them to $V\hat{a}r(\hat{\mu}_{EF})$. Of these

additional error sources, uncertainty arising from the prediction of each individual from the biomass model, and uncertainty resulting from a choice of alternative suitable models, are likely the major additional terms that should be considered for inclusion. The former of these diminishes with increasing sample size, and hence its importance is partially a function of the total number of individuals estimated. The latter error source is independent of sample size, and thus cannot be reduced by increased field effort. If alternative allometric models are available for a given situation, then it is recommended that the uncertainty due to model choice be considered for inclusion in the total error estimate. Measurement errors, such as errors in the estimation of stem diameter, are generally small so long as standard forestry protocols have been used.

A wide range of different methods can be used to estimate these additional allometric model error terms, including analytical approximations (e.g. Lo 2005, Ståhl et al., 2014), Monte-Carlo methods (e.g. Molto et al., 2013, Picard et al., 2015) and hybrid approaches (e.g. Chave et al., 2004). These additional error sources can combined into a single variance term, $Var(\hat{\mu}_{Allom})$, and added to $Var(\hat{\mu}_{EF})$ to provide an estimate of total error.

Box 27: Calculation of the uncertainty of emissions/removals factors under sampling with replacement

Sampling with replacement is a survey design where the measured change over time involves a combination of permanent and temporary sample plots. The estimate of the uncertainty of the difference between two time periods requires the following quantities:

n12: The number of 'common' or permanent plots across both t1 and t2.

n1: The total number of plots at t1.

n2: The total number of plots at t2.

n1- : The number of plots unique to t1.

n-2 : The number of plots unique to t2.

$s_{t_1}^2, s_{t_2}^2$: The variance of the measured carbon density at times t1 and t2.

r The plot-level correlation in carbon density between t1 and t2.

From this information two weighting parameters are calculated:

<div align="right">**Equation 32**</div>

$$A = \frac{n_{12}\left(rn_{-2} + n_1\right)}{n_1 n_2 - n_{-2} n_{1-} r^2}$$

<div align="right">**Equation 33**</div>

$$B = \frac{n_{12}\left(rn_{1-} + n_2\right)}{n_1 n_2 - n_{-2} n_{-1} r^2}$$

and the uncertainty of the estimate of the emissions/removals factor is given by:

<div align="right">**Equation 34**</div>

$$V\hat{a}r\left(\hat{\mu}_{EF}\right) = \frac{A^2 s_1^2 + B^2 s_1^2 - 2ABrs_1 s_2}{n_{12}} + \frac{\left(1-A\right)^2 s_1^2}{n_{1-}} + \frac{\left(1-B\right)^2 s_2^2}{n_{-2}}$$

When all of the plots measured at t1 are also measured at t2, then A = B = 1, and Equation 34 reduces to Equation 31. When there are no plots in common between t1 and t2, then A = B = 0, and Equation 34 reduces to Equation 30. In this latter case n12 = 0, and the first term in Equation 34 is undefined.

5.3 Estimating total emissions/removals and its uncertainty

In general terms, estimates of emissions and removals of carbon dioxide are made by summing differences in carbon density, multiplied by the area in which the change in carbon occurred. Generically one is dealing with terms of the type:

- ▶ Change in carbon between time t_1 and t_2 = (area of a given stratum) x (change in carbon density of the stratum)

or

- ▶ Change in carbon between time t_1 and t_2= (area transferred between two strata) x (change in carbon density between the strata)

Both areas and carbon densities have uncertainties which need to be combined with each other when estimating emissions or removals of carbon associated with each of the relevant pools (i.e. biomass, dead organic matter, litter and soil carbon). Similarly uncertainties for estimates of non-CO_2 greenhouse gas emissions are calculated by combining component emission/removal factors and activity data uncertainties.

The calculation for the uncertainty of area and change in area is described in Section 5.1.5 and is expressed as the variance in the estimate of the mean, denoted by $V\hat{a}r(\hat{\mu}_A)$. The calculation for the uncertainty in carbon density change is described in Section 5.2.5, and is given by $V\hat{a}r(\hat{\mu}_{EF})$.

The corresponding emissions, $\hat{\mu}_E$, are calculated as the product of the area and the emissions factor,

Equation 35

$$\hat{\mu}_E = \hat{\mu}_A \times \hat{\mu}_{EF}$$

If the units of $\hat{\mu}_E$ are in carbon, then the conversion to CO_2 is straightforwardly achieved by multiplying by 44/12.

Section 5.2.2.1 of GPG2003 cross-references section 6.3 of GPG2000[160] which describes Rule B for combining uncertainties when quantities are multiplied together, as in Equation 35. Rule B states the percentage uncertainty of the product is the square root of the sum of squares of the *percentage* uncertainties estimated for each of the quantities being multiplied. This rule is often used to calculate the variance of the product of two random, independent (i.e. uncorrelated) variables, it is an approximation. Goodman, (1960) derived an exact expression for the variance that requires no additional information to calculate, and which is given by:

Equation 36

$$V\hat{a}r(\hat{\mu}_E) = \hat{\mu}_{EF}^2 \times V\hat{a}r(\hat{\mu}_A) + \hat{\mu}_A^2 \times V\hat{a}r(\hat{\mu}_{EF}) + V\hat{a}r(\hat{\mu}_A) \times V\hat{a}r(\hat{\mu}_{EF})$$

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[160] Corresponding to volume 1, section 3.2.3.1 of 2006GL

Equation 36 requires are the estimates of the mean and the variance of the mean for area (A) and the emissions/removals factor. An example of the calculation of total emissions from activity data and emissions factors for a single stratum is given in Box 28: Applying uncertainty analysis to deforestation.

Often the required emissions estimate is one that combines N separate stratum-level estimates, to give a total estimate for all strata combined. In this case the total emissions is the sum of the total emissions for each stratum, $\sum \hat{\mu}_{E_i}$ ($i = 1..N$), with the variance of the estimate equal to $\sum V\hat{a}r\left(\hat{\mu}_{E_i}\right)$

For a given sampling density, the uncertainties associated with degradation, or removals as the result of forest growth in either MNF or planted forests, will be greater than those associated with deforestation estimates. If the uncertainty in biomass estimation exceeds the difference in carbon densities between the two sub-strata, the uncertainty of the degradation estimate will exceed 100%; in other words although the central estimate will remain that degradation in forest carbon stocks has occurred, there will be some possibility that there has actually been a gain.

Non-CO_2 greenhouse gas emissions associated with fire are estimated by multiplying emission/removal factors appropriate to the type of fire together with areas burnt and the amount of fuel combusted per unit area. Areas are estimated either by remote sensing from burn scars and have associated uncertainties, or from ground surveys. Emission/removal factors and uncertainty ranges are provided in Table 2.5 referenced in volume 1, section 2.4 of 2006GL[161]. The combined uncertainty associated with these emissions can be estimated using the equations for combining uncertainties given in Equation 30 and in Section 5.2.6

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[161] The method in section 3.2.1.4 of GPG2003 indexes non-CO_2 emissions from fire to emissions from CO_2 and does not provide default uncertainty ranges.

Box 28: Applying uncertainty analysis to deforestation

This example uses the results from the change in area due to deforestation calculation described in Box 24: A stratified approach to accuracy assessment and area estimation, and combines it with a hypothetical change in carbon density scenario.

Step 1. Change in area of deforested land.

The example in Box 24: A stratified approach to accuracy assessment and area estimation gives the total area of forest loss as 21,158 ha, with a standard error of 3,142 ha. The required quantities for calculating total emissions are:

$$\hat{\mu}_A = 21,158 \ ha$$

$$V\hat{a}r(\hat{\mu}_A) = 3,142^2 = 9,872.164$$

Step 2. Calculation of EF from the change in biomass density.

The carbon density of intact forest is assumed to be 250 tC/ha, with a standard error of 25 tC/ha (corresponding to an uncertainty of 10%). The carbon density of the post-clearing forest is assumed to be 30 tC/ha, with a standard error of 3 tC/ha (also corresponding to an uncertainty of 10%). The residual carbon in the post-clearing forest arises from e.g. slash residues, or patches of incomplete deforestation.

Assuming the field survey data underlying the carbon density estimates for pre- and post-deforestation involved independent sampling, then the calculation of change in biomass density and its uncertainty is,

$$\hat{\mu}_{EF} = (250 - 30) \times \frac{44}{12} = 807.4 \quad \text{t CO}_2\text{/ha}$$

$$V\hat{a}r(\hat{\mu}_{EF}) = \left(25 \times \frac{44}{12}\right)^2 + \left(3 \times \frac{44}{12}\right)^2 = 8539 \quad \text{[using Equation 28 from Section 5.2.6.2]}$$

The constant 44/12 is used to convert carbon density into units of CO_2

Step 3. Calculation of total emissions

The total emissions due to deforestation and its uncertainty are calculated using Equation 35 and Equation 36 respectively.

$$\hat{\mu}_E = 21,158 \times 807.4 = 17,082,970 \quad \text{t CO}_2$$

$$V\hat{a}r(\hat{\mu}_E) = (807.4)^2 \times 9872164 + (21,158)^2 \times 8,539 + 9,872,164 \times 8,539 = 1.034 \times 10^{13}$$

For this hypothetical example deforestation led to a loss of approximately 17.1 million tonnes of CO_2, with a standard error of $\sqrt{1.034 \times 10^{13}} = 3.2$ million tonnes of CO_2. The 95% confidence interval (as used in IPCC guidance and guidelines) is calculated as the standard error multiplied by 1.96, which yields the final result of 17.1 ± 6.3 million tonnes of CO_2, or a 95% confidence interval of 10.8 to 23.4 million tonnes CO_2.

Uncertainties may also be combined using probabilistic simulation (Monte-Carlo Analysis)[162] The Monte Carlo analysis is suitable for detailed category-by-category assessment of uncertainty, particularly where uncertainties are large, distribution is non-normal, the algorithms are complex functions and/or there are correlations between some of the activity sets, emissions factors, or both. Monte Carlo simulation requires the analyst to specify probability distribution functions (Fishman, 1996) that reasonably represent each model input for which the uncertainty is quantified. The probably distribution functions may be obtained by a variety of methods including statistical analysis of data or expert elicitation. A key consideration is to develop the distributions for the input variables to the emission/removal calculation model so that they are based upon consistent underlying assumptions regarding averaging time, location, and other conditioning factors relevant to the particular assessment (e.g. climatic conditions influencing agricultural greenhouse gas emissions). Monte Carlo analysis can deal with probability density functions of any physically possible shape and width, as well as handling varying degrees of correlation (both in time and between source/sink categories)[163].

If emissions and removals are estimated using a fully integrated system (Chapter 3, Section 3.2), rather than the simple multiplication of activity data and emissions/removals factors, then Monte-Carlo analysis may be the only feasible approach for estimating the uncertainties. The input data are the same as for the simple method just described, and (if data are available) the approach can also take account of auto- and cross-correlations, which cannot readily be included in the simple method. IPCC has shown[164] that, with the same input data, the simple method and probabilistic simulation give similar results.

Countries may need to estimate the uncertainty associated with a difference between an emissions or removals outturn and a FREL or FREL. Box 29: Uncertainty in the difference between a FREL/FRL and deforestation emissions during an assessment period presents a typical example of how to do this for deforestation, using the methods described in this section.

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[162] Section 5.2.2.2 of GPG2003 or volume 1, section 3.2.3.2 of 2006GL

[163] Volume 1, chapter 3, section 3.2.3 of 2006GL provides detailed guidance on Mote Carlo methods which are not repeated here.

[164] See volume 1 chapter 3, section 3.2.3.4 of 2006GL

Box 29: Uncertainty in the difference between a FREL/FRL and deforestation emissions during an assessment period

Suppose that to establish the FREL, a number N successive annual determinations of deforestation rate were made and that these had values $\hat{\mu}_{A_i}$ ha/yr (i=1…N), and that using the methods outlined in section Section 5.1.5, the uncertainty of each determination was estimated to be $V\hat{a}r\left(\hat{\mu}_{A_i}\right)$ corresponding to the variance of the mean deforestation rate (see also section Section 5.1.5). In this case, for the FREL the annual area deforested averaged over the N determinations is

Equation 37

$$\hat{\mu}_A = \frac{\sum \hat{\mu}_{A_i}}{N}$$

And, the successive determinations are uncorrelated, the corresponding uncertainty is

Equation 38

$$V\hat{a}r\left(\hat{\mu}_A\right) = \left(\frac{\sqrt{\sum V\hat{a}r\left(\hat{\mu}_{A_i}\right)}}{N}\right)^2$$

Similarly if during the assessment period, M successive determinations of the deforestation rate are made with values $\hat{\mu}_{B_j}$ ha/yr (j=1…M), each determination having an uncertainty of $V\hat{a}r\left(\hat{\mu}_{B_j}\right)$ again using the methods set out in section Section 5.1.5, the average annual deforestation rate during the assessment period is

Equation 39

$$\hat{\mu}_B = \frac{\sum \hat{\mu}_{B_i}}{N}$$

and the corresponding uncertainty is

Equation 40

$$V\hat{a}r\left(\hat{\mu}_B\right) = \left(\frac{\sqrt{\sum V\hat{a}r\left(\hat{\mu}_{B_i}\right)}}{N}\right)^2$$

Comparing the FREL and the assessment period, the difference in annual average deforestation rate is

Equation 41

$$\hat{\mu}_{A-B} = \hat{\mu}_A - \hat{\mu}_B$$

and using Equation 26 in Box 25: A model-assisted approach to accuracy assessment and area estimation the uncertainty of this difference is

Equation 42

$$\hat{Var}\left(\hat{\mu}_{A-B}\right) = \hat{Var}\left(\hat{\mu}_{A}\right) + \hat{Var}\left(\hat{\mu}_{B}\right)$$

Now suppose that the emissions/removals factor (the carbon density per unit area) is $\hat{\mu}_{EF}$ tCO_2 / ha with an uncertainty of $\hat{Var}(\hat{\mu}_{EF})$. The methods for calculating emissions/removals factors and their uncertainties are given in section Section 5.3, including the case where permanent plots (with correlated errors) are used in their calculation. Finally the mean annual difference in CO_2 emissions between the FREL and the assessment period is calculated as the difference in area multiplied by the emissions/removals factor

Equation 43

$$\hat{\mu}_{\Delta} = \hat{\mu}_{EF} \times \hat{\mu}_{A-B}$$

with the uncertainty of $\hat{\mu}_{\Delta}$ given in Equation 44, consistent with Equation 36:

Equation 44

$$\hat{Var}\left(\hat{\mu}_{\Delta}\right) = \hat{\mu}_{EF}^{2} \times \hat{Var}\left(\hat{\mu}_{A-B}\right) + \hat{\mu}_{A-B}^{2} \times \hat{Var}\left(\hat{\mu}_{EF}\right) + \hat{Var}\left(\hat{\mu}_{A-B}\right) \times \hat{Var}\left(\hat{\mu}_{EF}\right)$$

The result can also be expressed in terms of a 95% confidence interval

Equation 45

$$\hat{\mu}_{\Delta} \pm t_{0.95} \times \sqrt{\hat{Var}\left(\hat{\mu}_{\Delta}\right)}$$

5.4   Guiding principles – Estimation and uncertainty

▸ Image classification can be by human interpretation, or it can be automated with human interpreters checking the results. The latter can be less resource intensive and may increase consistency.

▸ The results of using a classification algorithm can be improved by an iterative process involving human interpretation, choice of training data, and use of auxiliary information usually obtained via the NFMS on forest conditions on the ground.

▸ Reference data should be used with map data to correct for estimated bias and estimate confidence intervals.

▸ The stratification used for activity data and for estimating emissions and removals factors should be consistent.

▸ In addition to the general principles of consistent representation of land when using remote sensing for representing land or tracking units of land using a pixel approach, MGD advice is that:

  › Once a pixel is included, then it should continue to be tracked for all time. This will prevent the double counting of activities in the inventory and will also make emissions estimates more accurate.

  › Stocks may be attributed to pixels, but only change in stocks and consequent emissions and removals are reported with attention to continuity to prevent the risk of estimating large false emissions and removals as land moves between categories.

  › Tracking needs to be able to distinguish both land cover changes that are land-use changes, and land cover changes that lead to emissions within a land-use category. This prevents incorrect allocation of lands and incorrect emissions or removals factors or models being applied that could bias results.

  › Rules are needed to ensure consistent classification by eliminating oscillation of pixels between land uses when close to the definition limits.

▸ In addition to classification errors, uncertainties arise from biomass and other sampling used to establish emissions and removals factors and other parameters, and use of default data.

▸ Combining activity data and emission factor uncertainties to estimate overall uncertainty estimates is possible using repeated application of straightforward rules, or (in the case of more complex modelling approaches) by Monte-Carlo analysis.

Chapter 6   Reporting and verification of emissions and removals

This chapter outlines the reporting and verification process of the UNFCCC as it relates to REDD+. The requirements for forest reference emission levels and technical annexes to the Biennial Update report are discussed separately.

6.1   REDD+ requirements and procedures

In general terms, reporting is the process of formal submission of results according to pre-established requirements, and verification is the process of assessing the data and information submitted. Reporting and verification processes can form part of quality assurance and quality control programs (Chapter 2, Section 2.3.4) and provide useful experience for the consideration of prioritising step-wise improvements.

This section outlines requirements that imply reporting and verification relevant to REDD+ under the UNFCCC. As defined by the COP decisions on REDD+ and represented in Table 19: Requirements under the UNFCCC REDD+ to access results-based payments.

Reporting and verification comprise a sequential process with initial submission and technical assessment of the FREL/FRL (Section 6.2 and Section 6.3), followed by reporting and analysis of emissions and removals associated with REDD+ activities consistent with the FREL/FRL (Section 6.4 and Section 6.5). Figure 14: FREL/FRL technical assessment process shows the Technical Assessment process for the FRLs/FRELs in more detail.

Table 19: Requirements under the UNFCCC REDD+ to access results-based payments

What countries need to have or provide	How to communicate to the UNFCCC	Process associated under UNFCCC	Timing	UNFCCC REDD+ platform Information hub	Decision
REDD+ National Strategy or Action Plan	No Need	None	In place when seeking RBP	As appropriated, link to the documents	1/CP.16, para (71a) 9/CP.19, para 3&11
National Forest Monitoring System	No Need	None	In place when seeking RBP	As appropriated, link to the documents	1/CP.16, para (71c) 11/CP.19, & Annex

What countries need to have or provide	How to communicate to the UNFCCC	Process associated under UNFCCC	Timing	UNFCCC REDD+ platform Information hub	Decision
National FREL/FRL	FREL/FRL submission	Technical Assessment on the context of RBP	When ready (especially when seeking RBP)	FREL/FRL submission and Technical Assessment Report	1/CP.16, para (71b) 12/CP.17(II), Annex 13/CP.19
Results in tCO$_2$e per year	Technical REDD+ Annex to the BUR	Technical Analysis of the Annex	After the FREL/FRL is assessed, same regularity as the BUR (2yrs)	Technical Analysis Report of the Annex	9/CP.19, para (3) & (11a,e) 14/CP.19, Annex
Safeguards (SG) information system	National Communication UNFCCC web platform	None	Summary of SG available when seeking RBP	When available or updated	1/CP.16, para (71d) 12/CP.17(I) 12/CP.19 17/CP.21
Source: modified from Iversen, 2014					

Figure 14: FREL/FRL technical assessment process
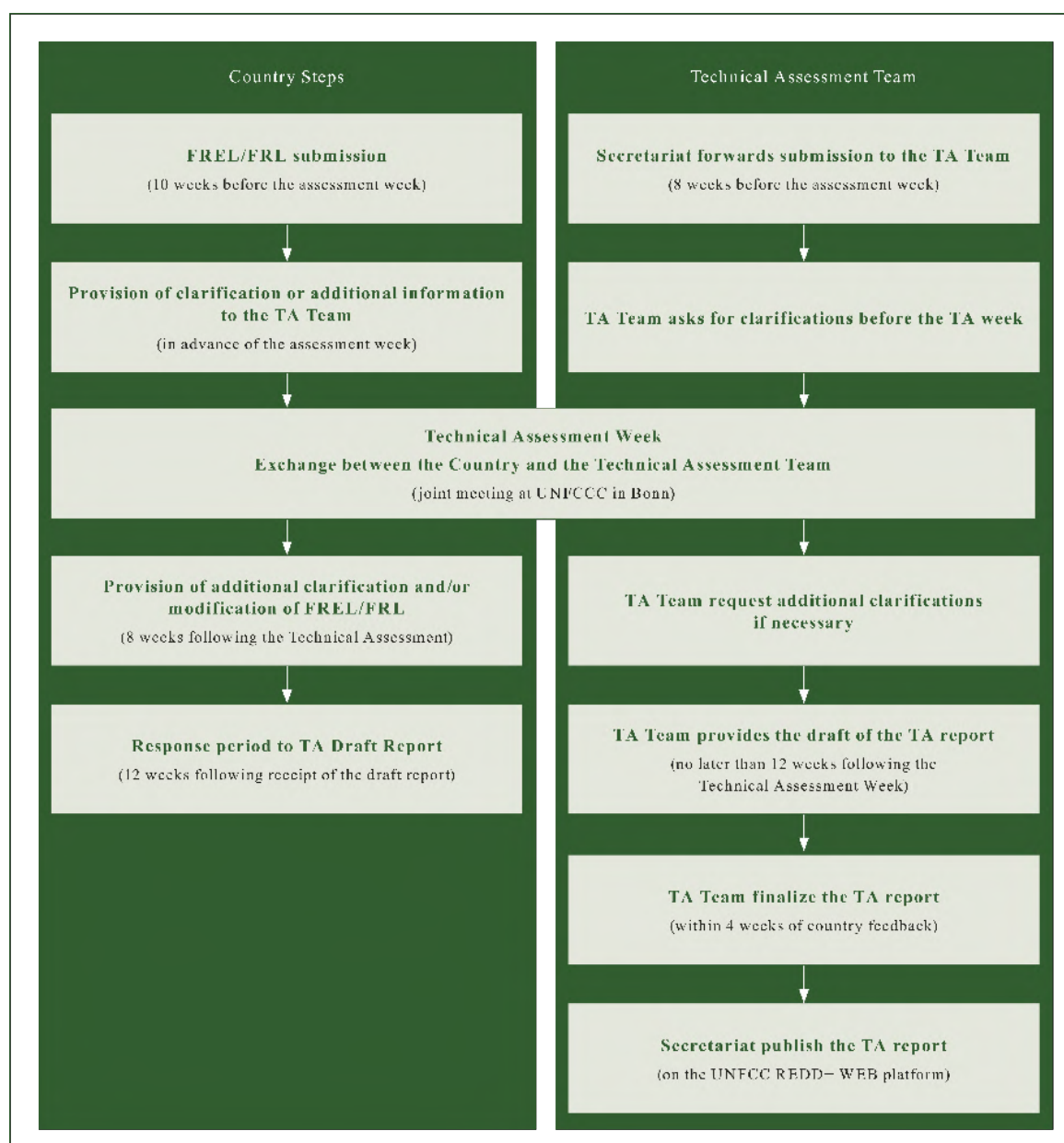
6.2 Reporting forest reference emission levels and forest reference levels

Decisions 12/CP.17 and 13/CP.19 invite countries to submit, voluntarily and in the context of results-based payments, proposed FREL/FRLs. These decisions address modalities for FREL/FRLs, established taking into account decision 4/CP.15 and maintaining consistency with each country's GHGI[(165)]. An

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[(165)] Maintaining consistency with National Greenhouse Inventory approaches for AFOLU reporting is vital to meeting the IPCC good practice principles (Chapter 2). Effective institutional arrangements that foster close coordination between agencies involved in REDD+ and National greenhouse Inventory reporting, where they are not the same agencies, will ensure effective use of resources and improve consistency in reporting (Chapter 1)

annex to 12/CP.17 specifies information to be submitted on the development of FREL/FRLs, including details of national circumstances (Chapter 2, Section 2.3.3 which discusses the interpretation of technical terms associated with FREL/FRLs).

The annex to decision 12/CP.17 says that information, amongst other things should:

▸ be guided by the most recent IPCC guidance and guidelines as adopted or encouraged by the COP;

▸ include in a comprehensive way information used in constructing the FREL/FRL, including historical data;

▸ be transparent, complete, consistent and accurate and include information on any changes from previous submissions;

▸ include pools, gases and activities listed in paragraph 70 of decision 1/CP.16 which have been included in the FREL/FRL and any reasons for omitting pools or activities from the construction of FREL/FRLs, noting that significant pools and/or activities should not be excluded;

▸ include the definition of forest used and if this is different from the definition used in the national greenhouse gas inventory or in reporting to other international organizations, an explanation why.

Submitted FREL/FRLs are published on the UNFCCC website, together with any updated versions of the FREL/FRLs made as a result of the technical assessment process, or subsequently[166].

6.3   Technical assessment of forest reference emission levels and forest reference levels

The objectives of the technical assessment of FREL/FRLs submitted under the provisions of decision 12/CP.17 are:

a. to assess the degree to which information provided by Parties is in accordance with the guidelines for submissions of information on FREL/FRLs contained in the annex to decision 12/CP.17; and

b. to offer a facilitative, non-intrusive, technical exchange of information on the construction of FREL/FRLs with a view to supporting the capacity of developing country Parties for the construction and future improvements, as appropriate, of their FREL/FRLs, subject to national capabilities and policy.

The scope of the technical assessment of FREL/FRLs, as defined in the annex to decision 13/CP.19, covers elements that Parties should present in their FREL/FRL, consistent with the guidelines for submission of reference levels detailed in the annex to decision 12/CP17.

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[166] Decision 12/CP.17, paragraph 12 states that '…a developing country Party should update a forest reference emission level and/or forest reference level periodically as appropriate, taking into account new knowledge, new trends and any modification of scope and methodologies.'

Parties are invited to submit transparent, complete[167], consistent and accurate information. In this context, the following will be considered during the technical assessment:

▸ the data, approaches, methods, models (if applicable) and assumptions used in the construction of the FREL/FRL

▸ consistency with corresponding anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks between the FREL/FRL and the national GHGI

▸ how historical data have been taken into account in the establishment of the FREL/FRL

▸ relevant policies and plans, as appropriate

▸ changes to any previously submitted FREL/FRL taking into account the stepwise approach[168]

▸ pools and gases, and activities included in the FREL/FRL, and justification of why omitted pools and/or activities were deemed not significant

▸ the definition of forest used, if it is the same used in the GHGs inventory or the reported to other international organizations and why and how the definition used was chosen

▸ whether the FREL/FRL is national, or covers less that the entire national forest area

▸ whether assumptions about future changes to domestic policies have been included in the construction of the FREL/FRL.

The results of the technical assessment are published on the UNFCCC web-site[169], together with the FREL/FRL submissions and any revised submissions resulting from the technical assessment.

6.4 Reporting results of REDD+ activities

According to decision 14/CP.19, data and information relating to implementation of REDD+ activities should be provided through Biennial Update Reports (BUR) on a voluntary basis in the context of accessing results based payments. Parties seeking results-based payments, that have already completed the technical assessment of their FREL/FRL, are requested to submit a REDD+ technical annex to the BUR, which should present the data and information used in the estimation of anthropogenic forest-related emissions by sources and removals by sinks, forest carbon stocks, and forest carbon stock and forest-area changes compared on a consistent basis with the established and assessed FREL/FRL. Based on the requirements outlined in annex to decision 14/CP.19, data and information provided in the REDD+ technical annex to the BUR are:

1. Summary information from the final assessment report of each FREL/FRL, which includes the:

   a. assessed FREL/FRL expressed in tCO$_2$eq per year

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[167] Complete means the provision of information that allows for the reconstruction of the forest reference emission levels and/or forest reference levels.

[168] Paragraph 10 of decision 12/CP.17 agreed that a step-wise approach to national [FREL and/or FRL] development may be useful, enabling Parties to improve the [FREL and/or FRL] by incorporating better data, improved methodologies and, where appropriate, additional pools, noting the importance of adequate and predictable support as referenced by paragraph 71 of decision 1/CP.16.

[169] See the UNFCCC REDD+ Web platform

b. REDD+ activity or activities included in the FREL/FRL

c. territorial forest area covered

d. date of the FREL/FRL submission and the date of the final technical assessment report

e. period (in years) of the assessed FREL/FRL.

2. Results in tCO_2eq per year, consistent with the assessed FREL/FRL;

a. Demonstration that the methodologies used to produce the results are consistent with those used to establish the assessed FREL/FRL

b. A description of the national forest monitoring system (NFMS) and the institutional roles and responsibilities for MRV of the results

c. Necessary information that allows for the reconstruction of the results

d. A description of how the elements contained in decision 4/CP.15, paragraph 1 (c)[170] and (d)[171], have been taken into account.

Decision 14/CP.19, paragraph 11a requires that the methodologies, definitions, comprehensiveness and the information submitted to the technical analysis should be consistent with those submitted to the technical assessment of the FREL/FRL.

Countries may wish to note that in the case of subnational monitoring and reporting of REDD+ activities, decision 1/CP.16, paragraph 71 (c) (recalled by decision 14/CP.19) requests monitoring and reporting on emissions displacement at the national level, if appropriate, as well as reporting on how displacement of emissions is being addressed, and on means of integration of subnational monitoring systems into the NFMS. In respect of 1(e) above the period referred to is presumably the period over which data were used to construct the FREL/FRL. Consistency as referred to in 3) above presumably entails that methodologies, data sources and assumptions submitted to the technical analysis should be the consistent with those submitted to the technical assessment. A more extensive discussion of technical terms related to FRELs and FRLs is presented in Chapter 2, Section 2.3.3.

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[170] To use the most recent Intergovernmental Panel on Climate Change guidance and guidelines, as adopted or encouraged by the Conference of the Parties, as appropriate, as a basis for estimating anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks, forest carbon stocks and forest area changes.

[171] To establish, according to national circumstances and capabilities, robust and transparent national forest monitoring systems and, if appropriate, subnational systems as part of national monitoring systems that:

    a. Use a combination of remote sensing and ground-based forest carbon inventory approaches for estimating, as appropriate, anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks, forest carbon stocks and forest area changes;

    b. Provide estimates that are transparent, consistent, as far as possible accurate, and that reduce uncertainties, taking into account national capabilities and capacities;

    c. Are transparent and their results are available and suitable for review as agreed by the COP;

6.5 Technical analysis of the REDD+ annex to the BUR

The technical analysis of the REDD+ technical annex to the BUR is conducted as part of the UNFCCC International Consultation and Analysis (ICA) process[172] (Box 30:UNFCCC international consultation and analysis (ICA) process).

Decision 14/CP.19 says that a technical annex to a BUR voluntarily submitted by a developing country in the context of REDD+ results-based payments is subject to the technical analysis of the ICA process as referred to in decision 2/CP.17, annex IV, paragraph 4. By this decision, upon the request of the developing country Party seeking to obtain and receive payments for REDD+ results-based actions, two experts, one each from a developing and a developed country Party, in land use, land-use change and forestry (LULUCF) from the UNFCCC roster of experts are to be included among the members selected for the Team of Technical Experts (TTE), which conducts a technical analysis of the BUR, for the technical REDD+ annex.

The material submitted in the REDD+ technical annex to the BUR, will be subject to technical analysis to analyse the extent to which:

▸ there is consistency in methodologies, definitions, comprehensiveness and the information provided between the assessed reference level and the results of the implementation of REDD+ activities[173];

▸ the data and information provided in the technical annex is transparent, consistent, complete (in the sense of allowing reconstruction) and accurate;

▸ the data and information consistent with the guidelines for preparing the technical annex contained in the annex to decision 14/CP.19;

▸ the results are accurate, to the extent possible.

As outlined in decision 9/CP.19, completion of the technical analysis of the technical annex by the LULUCF experts of the TTE is one of the requirements for a developing country Party to obtain and receive results-based finance.

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[172] The COP, by decision 1/CP.16, decided that developing countries would submit biennial update reports (BURs) (paragraph 60) and conduct international consultation and analysis (ICA) of the BURs (paragraph 63), through technical analysis by a team of technical experts (TTE) and facilitative sharing of views. The BUR reporting guidelines for Parties not included in Annex I to the Convention (non-Annex I Parties) as well as the modalities and guidelines for ICA were adopted at the seventeenth session of the Conference of the Parties (COP 17), by decision 2/CP.17 in annexes III and IV respectively.

[173] Applied methods and approaches need to be methodologically sound and follow scientific principles.

In accordance with decision 14/CP.19, paragraph 14, the LULUCF experts, under their collective responsibility in conducting the technical analysis of the REDD+ technical annex, will develop a technical report separate to the BUR ICA report. This technical report will contain:

- ▸ the technical annex submitted by the Party;

- ▸ analysis of the technical annex by the LULUCF experts;

- ▸ areas for technical improvement such as improvements to data and methodologies;

- ▸ any comments or responses by the Party concerned, including areas for further improvement and capacity-building needs.

This report, containing all the elements listed above, will be published by the secretariat on the UNFCCC REDD web platform.

Technical analysis is a facilitative process. The LULUCF experts can seek clarifications on the technical annex and the developing country Party should provide clarifications to the extent possible, in accordance with national circumstances and taking into account national capabilities.

Whilst the scope of the technical analysis does not include the Party's national REDD+ strategy and action plan[174], or the safeguards summary, these elements need to be provided in order to access results-based payments[175].

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[174] In the context of results-based payments, countries need to provide a link to their national strategy and/or action plan on the UNFCCC REDD web platform, as appropriate

[175] National strategies and action plans and the reporting on safeguards are excluded from the technical analysis, but the most recent summary information on how all REDD safeguards have been addressed and respected must be provided before Parties can receive REDD results-based payments, in accordance with decision 9/CP.19, paragraph 4.

> **Box 30: UNFCCC international consultation and analysis (ICA) process**
>
> The modalities and guidelines for conducting ICA were adopted in Durban (annex IV to decision 2/CP.17) and outline the requirements of the ICA process of the BURs (and any annexes). These requirements state that the ICA process:
>
> - Is non-intrusive, non-punitive, and respectful of national sovereignty;
>
> - Aims to facilitate the universal participation of developing country Parties in the ICA process;
>
> - Aims to increase the transparency[a] of mitigation actions and their effects;
>
> - Is a consultative approach through a facilitative sharing of views between the team of technical experts and the Party;
>
> - Does not include discussion on the appropriateness of domestic policies and measures;
>
> - Will result in a summary report.
>
> Notes: a. the purpose of transparency of action is to provide UNFCCC with c clear understanding of actions being taken by Parties including clarity and tracking of progress towards achieving Parties' individual nationally determined contributions. See Article 13 of the Paris Agreement.

6.6   Additional advice on REDD+ reporting and verification

Although not set out in COP decisions, to address the requirements of the technical analysis a country may wish as part of an internal verification process (Chapter 2, Section 2.3.4) to check that:

1. information on methodologies is communicated consistently between the most recent FREL/FRL submission and the REDD+ technical annex to the Biennial Update Report and any differences explained

2. the scope of the FREL/FRL and the estimates presented REDD+ technical annex are consistent with regard to territorial forest area, forest and other land use definitions, stratification, reported REDD+ activities and carbon pools[176]

3. data sources (i.e. sources of ground observations and remote sensing data) are transparently, consistently, completely and accurately applied in the generation of estimates for both the FREL/FRL and the REDD+ annex to the BUR[177]. Consistency between FREL/FRLs and GHGIs is covered in more detail in Chapter 2, Section 2.3.3.

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[176] This consistency will enable a robust and complete comparison between the FREL/FRL and reported emission reductions

[177] 'transparent' means that the assumptions and methodologies used should be clearly explained to facilitate replication and assessment of estimates by users of the reported information;

'consistent' means that estimates should be internally consistent in all elements over a period of years;

'complete' means the provision of information that allows for the reconstruction of the results;

'accurate' means estimates are systematically neither over nor under true emissions or removals, so far as can be judged, and that uncertainties are reduced so far as is practicable.

4. assumptions are transparently, consistently, completely and accurately reported for both the FREL/FRL report and the REDD+ annex to the BUR

5. the following information on the FREL is provided within the technical annex:

   a. a summary of the data values,

   b. methodologies applied, and the

   c. start and end date of the historical period

6. estimates provided in the technical annex are expressed in tonnes of CO_2 equivalent per year

7. the date of the FREL/FRL submission and the date of its final technical assessment report

8. a description of the NFMS including institutional roles and responsibilities for measuring, reporting and verifying the results, data collection processes are included[178], [179]

9. there is a description of how the NFMS enables the assessment of different types of forest in the country, including natural forest as defined by the Party[180],

10. in the case of subnational monitoring, an explanation is provided of how displacement of emissions and integration of subnational monitoring systems into national monitoring is being addressed.

11. a description is provided of how IPCC guidance and guidelines, have been used as the basis for estimating anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks, forest carbon stocks and forest area changes. Advice on the relationship between IPCC guidance and guidelines and estimation of REDD+ activities is presented in Chapter 3.

12. estimates are presented transparently, consistently, accurately to the extent possible, with uncertainties reduced, taking into account national capabilities and capacities

13. the results are available, suitable and presented completely to allow their reconstruction[181]

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[178] By referencing decision 4/CP.15, decision 14/CP.19, paragraphs 9 and 11c require Parties to use a combination of remote sensing and ground-based forest carbon inventory approaches for estimating, as appropriate, anthropogenic forest-related greenhouse gas emissions by sources and removals by sinks, forest carbon stocks and forest area changes.

[179] In accordance with decision 14/CP.19, paragraph 11c, a description of the data and information used in the NFMS should be provided in the technical annex. This description could include data collection processes and any relationships between the national LULUCF greenhouse gas inventory and related NAMAs (if any, as appropriate). It could also include a description of how the NFMS builds on existing systems and produces estimates that are transparent, consistent over time, and are suitable for measuring, reporting and verifying anthropogenic forest-related emissions by sources and removals by sinks, forest carbon stocks, and forest carbon stock and forest-area changes resulting from the implementation of the reported REDD+ activities.

[180] IPCC methods require forest classification and associated stratification and the area of each stratum. A description of the forest stratification, inclusive of natural forest, should be provided as part of the description of the NFMS.

[181] In accordance with decision 14/CP.19, paragraph 11b and 11c, the technical annex should present the necessary information that allows for the reconstruction of results. This requirement does not necessarily require the LULUCF experts to reproduce the results but rather assess whether enough information has been provided to allow for their reconstruction

Paragraph 15 of decision 14/CP.19 notes that results-based actions may be eligible for market-based approaches that could be developed by the COP and further modalities for verification could be developed in this context.

6.7 Guiding Principles – Reporting and verification of emissions and removals

▶ Effective reporting and verification processes require establishment of national capacity and good communication between the national institutions involved.

▶ Reporting and verification processes should aim for consistency in methodologies, definitions, comprehensiveness and the information provided between reported reference levels, results of the implementation of REDD+ activities and GHGI.

▶ Transparent, consistent, complete (in the sense of allowing reconstruction) and accurate data and information should be provided as part of the UNFCCC technical assessment and technical analysis processes.

▶ Sufficient information needs to be reported to enable third parties to be able to assess whether reporting requirements have been met.

▶ Internal and external technical experts should be used to assess the quality of information reported as well as of the overall effectiveness of the MRV system.

▶ Developing effective REDD+ reporting and verification can usefully be seen as part of a broader information system that supports sustainable development, and not simply as a necessity driven by COP decisions.

Chapter 7   References

Arevalo, P. (2016). A prototype MRV system for the Colombian Amazon compliant with IPCC Approach 3 for securing activity data. Boston, MA: Doctoral Disseration, Boston University.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., and Silva, J.N. (2005). Selective Logging in the Brazilian Amazon. *Science.* 310:480.

Asner, G.P., Powell, G.V.N., Mascaro, J., Knapp, D.E., Clark, J.K., Jacobson, J., Kennedy-Bowdoin, T., Balaji, A., Paez-Acosta, G., Victoria, E., Secada, L., Valqui, M. & Hughes, R.F. (2010). High-resolution forest carbon stocks and emissions in the Amazon. *Proceedings of the National Academy of Sciences,* 107: 16738-16742.

Australian Greenhouse Office (AGO). (2002). Greenhouse gas emissions from land use change in Australia: an Integrated Application of the National Carbon Accounting System.

Australian Government, (2011). The land sector in the National inventory – overview. Australian National Greenhouse Accounts. National Inventory.

Baldauf, T. (2013). Monitoring Reduced Emissions from Deforestation and Forest Degradation (REDD+): Capabilities of High-Resolution Active Remote Sensing. PhD Thesis, University of Hamburg.

Ballhorn, U., Siegert, F., Mason, M., & Limind, S. (2009): Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands; PNAS.

Barthelmes, A., Ballhorn, U. & Couwenberg, J. (2015). Practical guidance on locating and delineating peatlands and other organic soils in the tropics. Consulting Study 5 of the High Carbon Stock Study, 120 pp.

Birdsey, R., Angeles-Perez, G., Kurz, W.A., Lister, A., Olguin, M., Pan, Y., Wayson, C., Wilson, B., & Johnson, K. (2013). Approaches to monitoring changes in carbon stocks for REDD+. *Carbon Management,* 4(5): 519–537

Böttcher, H., Eisbrenner, K., Fritz, S., Kindermann, G., Kraxner, F., McCallum, I., & Obersteiner, M. (2009). An assessment of monitoring requirements and costs of 'Reduced Emissions from Deforestation and Degradation'. *Carbon Balance and Management*, 4:7.

Box, G.E.P, Jenkins, G.M., Reinsel, G.C. (1994). Time Series Analysis. Forecasting and Control. 4th Edition. Wiley & Sons. 784p. ISBN: 978-0-470-27284-8

Brack, C., Richards, G., & Waterworth, R.M. (2006). Integrated and comprehensive estimation of greenhouse gas emissions from land systems. *Sustainability Science*, 1(1): 91-106.

Breiman, L., Freidman, JH, Olshen, RA, & Stonem CJ. (1984). Classification and regression trees. Wadsworth, Belmont CA.

Breiman, L. (2001). Random Forests. *Machine Learning.* 45(1):5-32.

Brunet-Navarro, P., Jochheim, H., & Muys, B. (2016), Modelling carbon stocks and fluxes in the wood product sector: a comparative review. Global Change Biology, 22(7):2555-69.

Bryan, J.E., Shearman, P.L., Asner, G.P., Knapp, D.E., Aoro, G., & Lokes, B. (2013). Extreme Differences in Forest Degradation in Borneo: Comparing Practices in Sarawak, Sabah, and Brunei. PLoS ONE 8:7: e69679

Burslem, D.F.R.P & Ledo, A., (2015). Review of forest inventory methods for estimating forest biomass stocks. Consulting study 1. *High Carbon Stock science study* 39 pp.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., & Perez, R. (2004). Error propogation and scaling for tropical forest biomass estimates. *Philosophical Transactions of the Royal Society London B*. 359:409–420.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*. 145:78–99.

Chave, J., Rejou-Mechain, M., Burquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B. & Vielledent, G. (2014). Improved allometric models to estimate the above-ground biomass of tropical trees. *Global Change Biology*. 20:3177-3190.

Chen, J., Jönsson, P., Tamura, M., Gu, Z., Matsushita, B., Eklundh, L. (2004). A simple method for reconstructing a high-quality NDVI time series data set based on the Savitzky–Golay filter. *Remote Sensing of Environment*. 91(3-4):332-344.

Cienciala, E., Tomppo, E., Snorrason, A., Broadmeadow, M., Colin, A., Dunger, K., Exnerova, Z., Lasserre, B., Petersson, H., Priwitzer, T., Peña, G.S., & Ståhl G. (2008). Preparing emission reporting from forests: use of national forest inventories in European countries. *Silva Fennica*. 42(1): 73-88.

Cochran, W.G. (1977). Sampling techniques, 3rd ed. New York: Wiley. 428 pp

Cohen, W.B., Yang, Z., & Kennedy, R. E. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync - Tools for calibration and validation. *Remote Sensing of Environment*. 114(12):2911–2924.

Cohen, W.B., Yang, Z., Stehman, S.V., Schroeder, T.A., Bell, D.M., Masek, J.G., & Meigs, G.W. (2016). Forest disturbance across the conterminous United States from 1985–2012: The emerging dominance of forest decline. *Forest Ecology and Management*. 360:242-252.

DeVries, B., Decuyper, M., Verbesselt, J., Zeileis, A., Herold, M., Joseph, S. (2015) Tracking disturbance-regrowth dynamics in tropical forests using structural change detection and Landsat time series. *Remote Sensing of Environment*. 169:320-334.

Ene, L.T., Næsset, E., Gobakken, T., Gregoire, T.G., Ståhl, G. & Nelson, R. (2012). Assessing the accuracy of regional LIDAR-based biomass estimation using a simulation approach. *Remote Sensing of Environment*. 123:579-592.

FAO & JRC. (2012). Global forest land-use change 1990–2005, by E.J. Lindquist, R. D'Annunzio, A. Gerrand, K. MacDicken, F. Achard, R. Beuchle, A. Brink, H.D. Eva, P. Mayaux, J. San-Miguel-Ayanz & H-J. Stibig. FAO Forestry Paper No. 169. Food and Agriculture Organization of the United Nations and European Commission Joint Research Centre. Rome, FAO.

Fishman, G. 1996. Monte Carlo: Concepts, algorithms, and applications. New York. N.Y Springer.

FRA, 2015. Global Forest Resources Assessment 2015. Desk Reference. FAO. Rome. ISBN 978-92-5-108826-5.

Furby, S.L., Caccetta, P. A., Wu, X. & Chia, J. (2008). Australia's National Carbon Accounting System (NCAS) - Continental scale land cover change monitoring in Australia using Landsat imagery. Lesvos, Greece : International Conference on Studying, Modeling and Sense Making of Planet Earth.

Fry, J.A., Coan, M.J., Homer, C.G., Meyer, D.K., & Wickham, J.D. (2009). Completion of the National Land Cover Database (NLCD) 1992–2001 Land Cover Change Retrofit product: U.S. Geological Survey Open-File Report 2008–1379, 18 pp.

Gao, Y., & Francois Mas, J. (2008). A Comparison of the Performance of Pixel Based and Object Based Classifications over Images with Various Spatial Resolutions. *Online Journal of Earth Sciences.* 2:27-35.

GEO (2011) Observations, Group on Earth. GEO-FCT Product Development Team Technical Status Report v2.0. s.l. GEO.

GOFC-GOLD. 2015, A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation. GOFC-GOLD Report version COP21-1, (GOFC-GOLD Land Cover Project Office, Wageningen University, The Netherlands).

Goodman, L.A. 1960, On the exact variance of products. *Journal of the American Statistical Association.* 55:708-713.

Goslee, K.M., Brown, S., Walker, S.M., Murray, L. & Tepe, T. (2015). Review of aboveground biomass estimation techniques. Consulting Study 3. *High Carbon Stock science study.* 31pp

GPG 2000, GPG2003, 2006GL see Intergovernmental Panel on Climate Change

Gregoire, T.G., Ståhl, G., Næsset, E., Gobakken, T., Nelson, R., & Holm, S. (2011). Model-assisted estimation of biomass in a LIDAR sample survey in Hedmark County, Norway. *Canadian Journal of Forest Research.* 41:83-95.

Griffiths, P., Kuemmerle, T., Baumann, M., Radeloff, V. C., Abrudan, I. V., Lieskovsky, J., Munteanu, C.; Ostapowicz, K., & Hostert, P. (2014). Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. *Remote Sensing of Environment.* 151:72–88.

Hansen, M.C., Potapov, P.V, Moore, R., Hancher, M., Turubanova, S.A, Tyukavina, A., Thau, D., Stehman, V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., & Townshend, J.R.G. (2013). High-resolution global maps of 21st-century forest cover change. *Science.* 342(6160): 850–3. Data available online.

Heikkinen, J., Tomppo, E., Freidemschuss, A., Weiss, P., Hylen, G., Kušar, G., McRoberts, R., Kändler, G., Cienciala, E., Petersson, H., & Ståhl, G. (2012). Interpolating and extrapolating information from periodic forest surveys for annual greenhouse gas reporting. *Forest Science.* 58(3): 236-247.

Hoekman, D. (2012). Key Science Questions: Optimising information extraction from C-band SAR. Arusha, Tanzania : GEO FCT Science and Data Summit #3.

Holden, C.E. (2015). Yet Another Time Series Model (YATSM). Zenodo. 10.5281/zenodo.17129.

Holecz, F., Barbieri, M., Cantone, A., Pasquali, P., Monaco, S. (2010). K&C Science Report – Phase 1 Forest Theme – Synergistic use of ALOS PALSAR, ENVISAR ASAR and Landsat TM/ETM+ data for land cover and change mapping. Japan: JAXA, 2010. The ALOS Kyoto & Carbon Initiative – Science Team Reports Phase 1.

Houghton, R.A., F. Hall, F., & Goetz, S.J. (2009). Importance of biomass in the global carbon cycle, J. Geophys. Res., 114, G00E03,

Huang, C., Goward, S.N., Masek, J.G., Thomas, N., Zhu, Z., & Vogelman, J.E. (2010). An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sensing of Environment.* 114(1):183–198.

Huntzinger, D.N., Post, W.M., Wei, Y., Michalak, A.M., West, T.O., Jacobson, A.R., Baker, I.T., Chen, J.M., Davis, K.J., Hayes, D.J., Hoffman, F.M., Jain, A.K., Liu, S., McGuire, A.D., Neilson, R.P., Potter, Chris, Poulter, B.,Price, David, Raczka, B.M., Tian, H.Q., Thornton, P., Tomelleri, E., Viovy, N., Xiao, J., Yuan, W., Zeng, N., Zhao, M., and Cook, R. (2012). North American Carbon Project (NACP) regional interim synthesis: terrestrial biospheric model intercomparison. *Ecological Modelling.* 232:144–157.

Intergovernmental Panel on Climate Change (IPCC). (2000). Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen T., Meijer J., Miwa K., and Tanabe K. (Eds). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC/OECD/IEA/IGES, Hayama, Japan.

Intergovernmental Panel on Climate Change (IPCC) (2003). Penman J., Gytarsky M., Hiraishi T., Krug, T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K., and Wagner F (Eds*). Good Practice Guidance for Land Use, land- Use Change and Forestry* IPCC/IGES, Hayama, Japan.

Intergovernmental Panel on Climate Change (IPCC) (2006). Eggleston, S., Buendia L., Miwa K., Ngara T., and Tanabe K. (Eds*). 2006 IPCC Guidelines for National Greenhouse Gas Inventories* IPCC/IGES, Hayama, Japan.

Intergovernmental Panel on Climate Change (IPCC) (2014). *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds) Published: IPCC, Switzerland.

Intergovernmental Panel on Climate Change (IPCC) (2014). *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Published: IPCC, Switzerland.

Irish, R.R., Barker, J.L., Goward, S.N., & Arvidson, T. (2006). Characterization of the Landsat-7 ETM + Automated Cloud-Cover Assessment (ACCA) Algorithm. *Photogrammetric Engineering & Remote Sensing.* 72(10):1179–1188.

Kandel, P.N., Awasthi, K, Shrestha, S.M., Hawkes, M., Kauranne, T., Gautam, B., Gunia, K, Dinerstein, E. (2013). Monitoring aboveground forest biomass: a comparison of cost and accuracy between LIDAR-Assisted Multisource Programme (LAMP) and field-based Forest Resource Assessment (FRA) in Nepal. *International Conference on Forest, People and Climate: Changing Paradigm*. 28-30 August, Pokhara, Nepal.

Kennedy, R.E., Cohen, W.B., & Schroeder, T.A. (2007). Trajectory-based change detection for automated characterization of forest disturbance dynamics. *Remote Sensing of Environment.* 110:370–386.

Kennedy, R.E., Yang, Z., & Cohen, W.B. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms. *Remote Sensing of Environment.* 114(12):2897–2910.

Kennedy, R.E., Andréfouët, S., Cohen, W.B., Gómez, C., Griffiths, P., Hais, M., Healey, S.P., Helmer, E.H., Hostert, P., Lyons M.B., Meigs, G.W., Pflugmacher, D., Phinn, S.R., Powell, S.L., Scarth, P. Sen, S., Schroeder, T.A., Schneider, A., Sonnenschein, R., Vogelmann, J.E., Wulder, M.A, and Zhu, Z. (2014).

Bringing an ecological view of change to Landsat-based remote sensing. *Frontiers in Ecology and the Environment.* 12(6):339–346.

Kim, D., Sexton, J.O., Noojipady, P., Huang, C., Anand, A., Channan, S., Feng, M., & Townshend, J.R.G. (2014). Global, Landsat-based forest-cover change from 1990 to 2000. *Remote Sensing of Environment.* 155:178–193.

Köhl, M., Magnussen, S.S. & Marchetti, M. (2006). Tropical Forestry: Sampling methods. Remote Sensing and GIS multi-resource forest inventory. Springer.

Köhl, M., Scott, C.T., Lister, A.J., Demon, I., & Plugge, D. (2015). Avoiding treatment bias of REDD+ monitoring by sampling with partial replacement. *Carbon balance and Management.* 10:11.

Kurz, W.A., Stinson, G., Rampley, G.J., Dymond, C.C., & Neilson, E.T. (2008). Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences.* 105: 1551-1555.

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.

Kurz, W.A., Birdsey, R.A., Mascorro, V.S., Greenberg, D., Dai, Z., Olguín, M., & Colditz, R. (2016). Integrated Modeling and Assessment of North American Forest Carbon Dynamics: Tools for monitoring, reporting and projecting forest greenhouse gas emissions and removals. (Summary Report) Montreal, Canada: Commission for Environmental Cooperation. 23 pp.

Lambin, E.F., & Strahlers, A.H. (1994). Change-vector analysis in multitemporal space: a tool to detect and categorize land-cover change processes using high temporal-resolution satellite data. *Remote Sensing of Environment.* 48(2):231-244.

Lawrence, M., McRoberts, R.E., Tomppo, E., Gschwantner, T., & Gabler, K. (2010). Comparisons of national forest inventories. In: Tomppo, E., Gschwantner, T., Lawrence, M., & McRoberts, R.E. (eds). National forest inventories: pathways to common reporting. Dordrecht, Springer. pp. 19-32.

Lo, E. (2005). Gaussian error propagation applied to ecological data: Post-ice-storm-downed woody biomass. *Ecological Monographs.* 75:451-466.

Loetsch, F., & Haller K.E. (1964). Forest Inventory. Volume 1. Verlagsgesellschaft. Munchen; Scott, C.T. 1984. *Forest Science* 30:157-166.

Lucas, R., Armston, J., Fairfax, R., Fensham, R., Accad, A., Carreiras, J., Kelley, J., Bunting, P., Clewley, D., Bray, S., Metcalfe, D., Dwyer, J., Bowen, M., Eyre, T., Laidlaw, M., & Shimada, M. (2010). An Evaluation of the ALOS PALSAR L-Band Backscatter—Above Ground Biomass Relationship Queensland, Australia: Impacts of Surface Moisture Condition and Vegetation Structure. *IEEE Journal of Selected Topics in Applied Earth Observation and Remote Sensing.* 3:576-593.

Margono, B.A., Turubanova, S., Zhuravleva, I., Potapov, P., Tyukavina, A., Baccini, A., Goetz, S., & Hansen, M.C. (2012). Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. *Environmental Research Letters.* 7(3):034010.

Mascorro, V.S., Coops, N.C., Kurz, W.A., & Olguín, M. (2015). Choice of satellite imagery and attribution of changes to disturbance type strongly affects forest carbon balance estimates. *Carbon Balance and Management*. 10(1):30.

Masek, J.G., Vermote, E.F., Saleous, N.E., Wolfe, R., Hall, F.G., Huemmrich, K.F., Gao, F., Kutler, J., & Lim, T.-K. (2006). A Landsat Surface Reflectance Dataset for North America, 1990–2000. *IEEE Geoscience and Remote Sensing Letters*. 3(1):68–72.

de Mesquita Jnr, H.N. (2011). Law enforcement deforestation assessment. Japan: The ALOS Kyoto and Carbon Initiative - Science Team Reports Phase 2 (2009-2011).

McRoberts, R.E., Holden, G.R., Nelson, M.D., Liknes, G.C., & Gormanson, D.D. (2006). Using satellite imagery as ancillary data for increasing the precision of estimates for the Forest Inventory and Analysis program of the USDA Forest Service. *Canadian Journal of Forest Research*. 36:2968-2980.

McRoberts, R.E. (2010). Probability- and model-based approaches to inference for proportion forest using satellite imagery as ancillary data. *Remote Sensing of Environment*. 114:1017-1025.

McRoberts, R.E. (2013). Post-classification approaches to estimating change in forest area. *Remote Sensing of Environment.* 151:149-156.

McRoberts, R.E., Gobakken, T., & Næsset, E. (2013). Inference for LIDAR-assisted estimation of forest growing stock volume. *Remote Sensing of Environment*. 128:268-275.

McRoberts, R.E. (2014). Post-classification approaches to estimating change in forest area. *Remote Sensing of Environment.* 151:149-156.

McRoberts, R.E., Vibrans, A.C, Sannier, C., Næsset, E., Hansen, M.C., & Lingner, D.V. (2016). Methods for evaluating the utilities of local and global maps for increasing the precision of estimates of subtropical forest area. *Canadian Journal of Forest Research.* 10:924-932.

Mitchard, E. (2015). Synthesis of the state of the art of above-ground biomass estimation using remote sensing. Consulting study 9. *High Carbon Stock science study*. 24 pp.

Mitchell, A.L., Tapley, I., Milne, A.K., Williams, M., & Lowell, K.(2012). GEO Forest Carbon Tracking Tasmania National Demonstrator: Radar Processing Methodologies for the Generation of Wall-to-Wall Mosaics Technical document prepared for the Department of Climate Change and Energy Efficiency (DCCEE), Vol II.

Mitchell, 2014. Joint GFOI/GOFC-GOLD R&D Expert Workshop on approaches to monitoring forest degradation for REDD+. University of Wageningen. The Netherlands – Oct 1-3, 2014.

Molto, Q., Rossi, V., & Blanc, L. (2013). Error propagation in biomass estimation in tropical forests. *Methods in Ecology and Evolution*. 4(2):175-183.

Næsset, E., Bollandsås, O.M., Gobakken, T., Gregoire, T.G., & Ståhl. G. (2013). Model-assisted estimation of change in forest biomass over an 11 year period in a sample survey supported by airborne LIDAR: A case study with post-stratification to provide activity data. *Remote Sensing of Environment*. 128:299-34.

Olofsson, P., Foody, G.M., Stehman, S.V., & Woodcock, C.E. (2013). Making better use of accuracy data in land change studies: estimating accuracy and area and quantifying uncertainty using stratified estimation. *Remote Sensing of Environment*. 129:122-131.

Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., & Wulder, M.A. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment.* 148:42-57.

Olofsson, P., Holden, C. E., Bullock, E. L., & Woodcock, C. E. (2016). Time series analysis of satellite data reveals continuous deforestation of New England since the 1980s. *Environmental Research Letters.* 11(6):064002.

Päivinen, R., & Yli-Kojola. H. (1989). Permanent sample plots in large-area forest inventory. *Silva Fennica.* 23:243-252.

Pandey, D. (2008). India's biennial forest cover mapping program - *National Forest Inventory in India.* Paris, France : COMIFAC Workshop on Monitoring of reduction of emissions from forest degradation.

Paul, K.I., Roxburgh, S.H., Chave, J., England, J.R., Zerihun, A., Specht, A., Lewis, T., Bennett, L.T., Baker, T.G., Adams, M.A., Huxtable, D., Montagu, K.D., Falster, D.S., Feller, M., Sochacki, S., Ritson, P., Bastin, G., Bartle, J., Wildy, D., Hobbs, T., Larmour, J., Waterworth, R., Stewart, H.T.L., Jonson, J., Forrester, D.I., Applegate, G., Mendham, D., Bradford, M., O'Grady, A., Green, D., Sudmeyer, R., Rance, S.J., Turner, J., Barton, C., Wenk, E.H., Grove, T., Attiwill, P.M., Pinkard, E., Butler, D., Brooksbank, K., Spencer, B., Snowdon, P., O'Brien, N., Battaglia, M., Cameron, D.M., Hamilton, S., McAuthur, G., & Sinclair, J. (2016). Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. *Global Change Biology.* 22(6):2106–2124.

Pérez-Cruzado, C., Fehrmann, L., Magdon, P., Cañellas, I., Sixto, H., & Kleinn, C. (2015). On the site-level suitability of biomass models. *Environmental Modelling & Software.* 73:14-26.

Picard, N., Bosela, F.B., & Rossi, V. (2015). Reducing the error in biomass estimates strongly depends on model selection. *Annals of Forest Science.* 72:811-823.

Pilli, R., Grassi, G., Kurz, W., Viñas, R., & Guerrero, N. (2016). Modelling forest carbon stock changes as affected by harvest and natural disturbances. I. Comparison with countries' estimates for forest management. *Carbon Balance and Management.* 11:5.

Reiche, J., Verbesselt, J., Hoekman, D., & Herold, M. (2015). Fusing Landsat and SAR time series to detect deforestation in the tropics. *Remote Sensing of Environment.* 156:276–293.

Roxburgh, S.R., Paul, K.I., Clifford, D., England, J.R., & Raison, R.J. (2015). Guidelines for constructing allomtric models for the prediction of woody biomass: How many individuals to harvest? *Ecosphere.* 6(3):38.

Roy, D.P., Ju, J., Kline, K., Scaramuzza, P.L., Kovalskyy, V., Hansen, M., Loveland, T.R., Vermot, E., & Zhang, C. (2010). Web-enabled Landsat Data (WELD): Landsat ETM+ composited mosaics of the conterminous United States. *Remote Sensing of Environment.* 114(1):35–49.

Saatchi, S. (2015). Mapping tropical forest biomass: Synthesis of ground and remote sensing inventory. Consulting Report 2. *High Carbon Stock science study.* 82pp

Sannier, C., McRoberts, R.E., Fichet, L.-V., & Makaga, E. (2014). Using the regression estimator with Landsat data to estimate proportion forest cover and net proportion of deforestation in Gabon. *Remote Sensing of Environment.* 151:138-148.

Sannier, C., McRoberts, R.E., & Fichet, L.-V. (2016). Suitability of Global Forest Change data to report forest cover estimates at national level in Gabon. *Remote Sensing of Environment.* 173:326-338.

Särndal, C.-E., Swensson, B., & Wretman, J. (1992). Model assisted survey sampling. Springer, New York. 693 pp.

Scaramuzza, P.L., Bouchard, M.A., & Dwyer, J.L. (2012). Development of the Landsat Data Continuity Mission Cloud-Cover Assessment Algorithms. *IEEE Transactions on Geoscience and Remote Sensing.* 50(4):1140–1154.

Smyth, C.E., Stinson, G., Neilson, E., Lemprière, T.C., Hafer, M., Rampley, G.J., & Kurz, W.A. (2014). Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences.* 11:441-480.

Souza Jr, C. (2006). Brazil's PRODES system - Mapping and monitoring deforestation and forest degradation in the Brazilian Amazon. Jena, Germany : GOFC-GOLD Symposium on Forest and Land Cover Observations.

Souza Jr, C, Siqueira J.V., Sales, M.H., Fonseca, A.V., Ribeiro J.G., Numata, I., Cochrane, M.A., Barber, C.P., Roberts, D.A,. & Barlow, J. (2013). Ten-Year Landsat Classification of Deforestation and Forest Degradation in the Brazilian Amazon. *Remote Sensing.* 5(11):5493-5513.

Ståhl, G., Heikkinen, J., Petersson, H., La, J.R., & Holm, S. (2014). Sample-Based Estimation of Greenhouse Gas Emissions From Forests-A New. Approach to Account for Both Sampling and Model Errors. *Forest Science.* 60:3-13

Stehman, S.V. (2013). Estimating area from an accuracy assessment error matrix. *Remote Sensing of Environment.* 132:202-211.

Stephens, P.R., Kimberley, M.O., Beets, P.N., Paul, T.S.H., Searles, N., Bell, A., Brack, C., & Broadley, J. (2011). Airborne scanning LiDAR in a double sampling forest carbon inventory. *Remote Sensing of Environment.* 117:348-357.

Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., Boisvenue, C., Rampley, G.J., Li, Q., White, T.M., & Blain, D. (2011). An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology.* 17:2227–2244.

Tomppo, E., Gschwantner, T., Lawrence, M., & McRoberts, R.E. (eds.). (2010). National forest inventories: pathways for common reporting. Heidelberg: Springer. 611 p.

Trofymow, J.A., Stinson, G., & Kurz, W.A. (2008). Derivation of a spatially explicit 86-year retrospective carbon budget for a landscape undergoing conversion from old-growth to managed forests on Vancouver Island, BC. *Forest Ecology and Management.* 256:1677–1691.

Verbesselt, J., Hyndman, R., Newnham, G., & Culvenor, D. (2010). Detecting trend and seasonal changes in satellite image time series. *Remote Sensing of Environment.* 114:106-115.

Verbesselt, J., Zeileis, A., & Herold, M. (2012). Near real-time disturbance detection using satellite image time series. *Remote Sensing of Environment.* 123:98–108.

Walker, W.S., Stickler, C.M., Kellndorfer, J.M., Kirsch, K.M., & Nepstad, D.C. (2010). Large-area classification and mapping of forest and land cover in the Brazilian Amazon: a comparative analysis of ALOS/PALSAR and Landsat data sources. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing.* 3:594-604.

Waterworth, R.M., & Richards, G.P. (2008). Implementing Australian forest management practices into a full carbon accounting model. *Forest Ecology and Management.* 255:2434-2443.

Winrock International. (2012). A Pilot Study to Assess Forest Degradation Surrounding New Infrastructure. Report submitted to the Guyana Forestry Commission February 2012.

Woodcock, C.E., Macomber, S.A., Pax-Lenney, M., & Cohen, W.B. (2001). Monitoring large areas for forest change using Landsat: Generalization across space, time and Landsat sensors. *Remote Sensing of Environment*. 78(1): 94-203.

Woodcock, C.E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., & Wynne, R. (2008). Free access to Landsat imagery. *Science*. 320(5879):1011-1012.

Wulder, M.A,, White, J.C., Loveland, T.R., Woodcock, C.E., Belward, A.S., Cohen, W.B., Fosnight, G., Shaw, J., Masek, J.G., & Roy, D.P. (2015). The global Landsat archive: Status, consolidation, and direction. *Remote Sensing of Environment*.

Xin, Q., Olofsson, P., Zhu, Z., Tan, B., & Woodcock, C.E. (2013). Toward near real-time monitoring of forest disturbance by fusion of MODIS and Landsat data. *Remote Sensing of Environment*. 135(86):234–247.

Zhuravleva, I., Turubanova, S., Potapov, P., Hansen, M., Tyukavina, A., Minnemeyer, S., Laporte, N., (2013). Satellite-based primary forest degradation assessment in the Democratic Republic of the Congo, 2000–2010. *Environmental Research Letters*. 8(2):024034.

Zhu, Z., Woodcock, C.E., & Olofsson, P. (2012). Continuous monitoring of forest disturbance using all available Landsat imagery. *Remote Sensing of Environment*. 122:75–91.

Zhu, Z., & Woodcock, C.E. (2012). Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment.* 118:83–94.

Zhu, Z., & Woodcock, C.E. (2014a). Continuous change detection and classification of land cover using all available Landsat data. *Remote Sensing of Environment*. 144:152–171.

Zhu, Z., & Woodcock, C.E. (2014b). Automated cloud, cloud shadow, and snow detection in multitemporal Landsat data: An algorithm designed specifically for monitoring land cover change. *Remote Sensing of Environment*. 152:217–234.

Zhu, Z., Wang, S., & Woodcock, C.E. (2015). Improvement and expansion of the Fmask algorithm: cloud, cloud shadow, and snow detection for Landsats 4–7, 8, and Sentinel 2 images. *Remote Sensing of Environment*. 159:269–277.

Appendices

Appendix A   Financial considerations

NFMS and associated measurement, reporting and verification processes have technical and administrative costs for their establishment and operation. These costs are affected by national circumstances. They vary over time and should be considered during the design decision stage.

There are potential cost efficiencies are to be gained by considering the framework established for forest monitoring for results-based-payments as an opportunity to establish an NFMS that meets a broader range of monitoring and reporting requirements. Costs incurred for remote sensing analyses or field sampling should be considered as not only an investment for REDD+, but also as a normal process of gathering relevant multifunctional national level data.

Establishment costs are once-off costs. They will depend on the methodological approach adopted and the amount of infrastructure and data already available. Operational costs are on-going or recurring costs to generate repeated REDD+ emission and removal estimates. Operational costs need to be considered during initial system design, and can be often be reduced by joint use of remote sensing and ground observations. A long-term view of costs and benefits will help avoid design decisions which are cheaper in the short-term, but which are more costly or unsustainable in the long-term.

Establishment costs

It is not easy to generalize about establishment costs, but the World Bank FCPF has estimated costs of readiness preparation activities provide an indication for the establishment of a FREL and maintenance of MRV processes. These are total budget estimates for the 10 year period, not annualized costs. The average is just over USD 4.5M (Table A1).

Costs associated with the more technical aspects of establishment can include:

▸ Facility rooms or laboratories within which technical work is conducted (this may use existing space) - estimated up to USD 1M

▸ Remote Sensing and Geographic Information System hardware and software (e.g. ~5-15 workstations depending on the geographic area, Idrisi/ENVI/ESRI type remote sensing software, ArcGIS Enterprise System) - estimated up to USD 200K. Open source freely available RS/GIS software options are also available

▸ Ground-based measurement equipment including vehicles, GPS, data recorders - estimated costs can exceed USD 500K.

Table 20: Estimated costs of FCPF Readiness Preparation Activities

Readiness component	Indicative readiness preparation budget for a 10 year period (USD)		
	Average	**Min**	**Max**
Reference Level	$1,435,000	$575,000	$3,000,000
MRV	$3,193,000	$1,106,000	$8,915,000
Total	$4,628,000		
Notes: Figures represent average, minimum and maximum budgets across 8 countries for reference level figures and 10 countries for MRV figures. Countries from Africa, Asia and the Americas included in all estimates.			

Operational costs

Acquisition of remote sensing data can represent an establishment as well as an operational cost. Through the CEOS SDCG much useful satellite data are now available at little to no cost to the user and countries are making use of the data, mainly Landsat in developing their FREL or FRL. If necessary data can be commissioned or purchased from commercial providers for specific purposes. Costs vary widely depending on e.g. source, resolution or any available discounts for volume purchases. A country might anticipate an initial high volume data requirement during its start-up phase as it establishes a forest reference emission level and determines which data combination best suits its requirements. Because of UNFCCC biennial reporting requirements are countries are developing monitoring systems designed for at least bi-annual updates of the activity data (often based on Landsat or other freely available data) plus NFI data collection every 5 - 10 years.

Collection of ground data may be required in both the establishment and ongoing operation. Depending upon reported REDD+ activities, carbon pools included and the level of existing information, a considerable number of new field observations may be needed. If a country has an established NFI the need for additional investment will depend on the capacity of the NFI to meet the additional needs of REDD+ MRV.

Recurring costs are largely those that any operational program would encounter. In general there will be need for:

▸ Clerical/administrative staff

▸ Field-based staff for ground-based data collection

▸ GIS/RS specialists (includes integration of remote sensing with ground observations)

▸ Facility costs including rent, utilities, maintenance, and insurance

▸ Expert consulting and implementation costs related to any identified NFMS improvements

Staff or contractors will not necessarily need to focus on REDD+ continuously. The periodic nature of assembling information into reports may tempt countries to contract much of its routine work to technical companies/organisations rather than maintain dedicated staff, although in this case it will be important to maintain sufficient expertise within the NFMS to interact effectively with the contracted organizations, and ensure value-for-money.

Appendix B   Sampling

Robust and reliable estimation of carbon in forest systems based on sampling must consider the following principles:

Identifying population units

The population is the total number of items, or units under consideration. Population units being sampled can range from plots to trees to points. Whatever type is chosen, the population units must be clearly identifiable, and any exclusions and their treatment noted. When sampling to calibrate an allometric model for example, the logical unit is a tree, but care is needed to deal with different parts – e.g. for the roots what is the practical minimum diameter to be considered? Plots for measuring forest stand characteristics can vary in size with examples ranging from 0.01 ha to over 1 ha, and can also include clusters of sub-plots (related to each other through their spatial placements) or designs where size-based sub-populations are only measured on parts of a plot. Plot shape can be related to remotely sensed data attributes (e.g. pixel size of optical sensors) and are usually rectangular, square or circular. Optimum size and shape of plots will vary with forest conditions, with small area plots more typical in relatively homogeneous populations while larger plots are required in tropical forests where large trees result in high spatial variation in biomass. The combination of field and RS data may require larger plots, to achieve correspondence between ground conditions and the minimum mapping unit.

Selecting which individuals in the population to sample

Individuals are selected for either of two general sampling approaches – probability-based or model-based.

Probability-based approaches rely on the ability to assign a probability of selection to each individual in the population. With such probability samples, sample-based estimates of parameters such as the mean or total can be inferred to represent the entire population. For example, simple random sampling, the most basic of these designs, assigns an equal probability to each individual. More efficient design-based approaches may be employed when some structure in the population can be reliably identified. For example, stratified sampling uses strata of relatively homogenous sub-populations to improve the efficiency of a given sampling effort. Design-based (or probability-based) inference requires probability samples, whereas model-based inference can use, but does not require, probability samples.

Model-based sampling can be used to select individuals to help parameterize a model. For this purpose, individuals do not need to be selected using a probability-based design, but rather are often selected to cover the range over which the model will be applied. Individuals may be selected to cover critical locations in the model domain, e.g. at the extremes, inflection points or where straight line relationships are anticipated. The way the individuals for measurement are identified and located should be transparent. Once the model has been constructed, it can be used with model-based inference to infer estimates of population parameters.

These two approaches are not mutually exclusive, e.g. model-based approaches have been used within design-based approaches like stratified random sampling (Wood & Schreuder, 1986). Box 31: Design and model -based sampling provides more detail on design-based and model-based sampling.

Box 31: Design and model -based sampling

Design-based sampling, also known as probability-based sampling, is a widely-known sampling system. In this system, sample locations are selected by a pre-determined random (probability based) process. The most frequent examples are simple random sampling, systematic sampling with a randomly selected starting point, and stratified random sampling, but cluster, double and sequential sampling approaches are also common. Every possible location must have a probability greater than zero of selection into the sample with the randomization process determining the particular sample locations. The probabilities are the sole basis for drawing conclusions or "inferences" - usually formulated as probability statements - from the sample about the population size (total, mean), proportion of the population with given characteristics (such as disturbance or occurrence of a rare species), or variance. This means that, if a sample is selected correctly according to the chosen random design, any inference based on these probabilities is valid and calculations do not rely on any assumption about the spatial distribution or other pattern in the population. Apart from measurement and observation errors and the errors from using allometric models, sampling is the only source of stochasticity considered and the effects of this uncertainty can be readily calculated. NFIs are typical probability-based sampling systems with plots established on systemic grids (with or without stratification) where the probability of selection for each plot (within a stratum) is equal and known. Probability sampling designs do not preclude unequal probabilities of selection into the sample. Examples include sampling proportional to, size (as in point sampling or variable radius sampling) or proportional to a prediction (estimated volume or height as in 3P sampling – Probability Proportional to Prediction).

Model-based sampling systems hypothesise the existence of a model that relates predictor (X or independent) variables to the response (Y, or dependent) variables of interest. A sample is drawn to allow inferences about this model, and the distribution of data around the model predictions. Two types of inference are therefore made under model-based sampling, concerning: (i) the values at locations unvisited during sampling; and (ii) parameters of the model, including the confidence intervals of the parameterised model. Estimates of the mean Y in a model-based system would be based on the inferences about the model at the value of the mean X. For example, a model-based system that uses LIDAR as a predictor variable might rely on an assumption that biomass is linearly related to the mean height above the ground of the returns per unit area. A purposive sample of field locations could be drawn to parameterise this model and the mean biomass of the forest could be estimated from this parameterised model and the mean LIDAR return over the entire forest. Accuracy of these estimates would depend on the legitimacy of the assumed model and the actual sample locations (within the model space). Inferences at specific locations could also be made although these will be less precise than the population mean estimates. Model-based systems do not assume that the probabilities of any sample location (pair of X and Y variables) are determined by the design, but rather they are an outcome of the chosen random model – for any given X, the Y values are likely to be centred around the model mean. Where the variation in Y around the model prediction is less than the total variation in Y, model-based systems can provide increased precision of estimates.

Selecting the number of individuals to sample

Sample size

To select a ground sample, the first step is to determine the sample size which is usually predetermined (sample size, n). Predetermined sample size approaches include those where: (i) the sample size is fixed

by the available budget or need to have historical consistency; (ii) a systematic approach is adopted to sample selection (e.g. by use of spatial grid of pre-determined resolution); (iii) a predetermined estimate has been made of the number required to produce usefully precise estimates. Predetermined sample sizes to produce usefully precise estimates for the targeted population (or sub-population or stratum), or for parameter estimation in the case of model-based sampling, must be based on estimates of the variability of the (sub-) populations, which may be available from existing data or reconnaissance surveys. Useful estimates are often defined in terms of the precision desired which in many cases is taken to be 10% as a default at the 95% confidence interval. The estimated sample size required under simple random sampling of a population (or a stratum within a population) is:

$$n = \frac{t^2 \sigma^2}{P^2}$$

where σ is the sample standard deviation expressed as a percentage of the mean when the sample is used alone to produce an estimate or σ is the standard deviation of the residual errors if the sample is used in combination with auxiliary data (e.g. remotely sensed data or existing maps) to produce an estimate, P is half the width of the interval, also expressed as a percentage of the mean and t is taken from the t distribution with degrees of freedom equal to n minus the number of parameters being estimated, at the confidence desired, commonly 0.05 corresponding to 95% confidence. Sample sizes to detect rare occurrences (e.g. disturbance in forests such as deforestation) may need to be relatively large under simple random sampling designs. For example, a sample of size of $n > 300$ is required if annual levels of forest disturbance were expected to be only about 1% of the population units , and sample units were selected via simple random sampling. Stratified sampling can increase efficiency significantly.

Supplementary sampling

Supplementary sampling may be used where an NFI or other extensive plot-based measurement system with a predefined sample size is already in place but does not adequately cover the whole population, or results in a precision that is too small to be reliable for the proposed forest monitoring system. Given the need for random selection (ability to determine the individuals to be selected) in probability sampling, the selection of additional sample units will be difficult in some circumstances. Where a systematic approach to sampling was originally used (e.g. sample locations at the intersection of a regularly spaced grid that was randomly overlaid on the population), additional sampling points can be assigned as an extension of that grid into areas originally excluded. Such an extension is particularly relevant when individuals in the original sample had been excluded due to tenure (e.g. by not including land managed by an Agricultural or Conservation Department even though it included forest by the national definition). The extended areas should maintain a separate identity if a stratified approach is used, but the systematic grid may be manipulated (e.g. only select every 2nd intersection) to ensure the sample size within the new stratum is appropriate (the number of samples per ha does not need to be constant between strata). Alternatively, if the stratum boundaries have not altered since the original sample but it has been determined that the precision of the stratum parameter estimates is insufficient, additional sample units can be selected using the original sampling approach (e.g. truly random or, more commonly re-laying the same systematic grid but randomly choosing additional intersection points).

Where the original sample was not systematic and the population or strata boundaries have changed, it is difficult to add sample units under a design-based approach. One possibility could be to draw an entirely new probability sample, calculate estimates from each sample separately, and then combine

the estimates. Otherwise a model-based approach may be more appropriate. The original sample data may be used to parameterise the hypothesized model, with additional sample units chosen to improve the precision of the inferences about that model. For example, the original sample may be used to parameterise a model that relates LIDAR data or canopy characteristics to plot measurements of carbon. Additional plots should be established in strata not included in the original sample to ensure the hypothesised model is appropriate for the extended population. Under a model-based system, the additional sample units need not use the original method of sample selection as inferences are not based on the selection design. Consequently if the inferences about the model are insufficiently precise (e.g. confidence limits of the model around the strata mean are too wide) then additional, ad hoc, sample points can be added provided they use the same plot measurement protocols of the original sample. Under a model-based approach using a linear model, additional sample units that add the most information tend to be those measured at the extremes of the independent value range (e.g. tallest forests as determined by LIDAR) although sampling covering the full range of dependent variables, irrespective of how the underlying population is clumped along this range, is useful to ensure the model is appropriate.

Using sample measurements to make inferences about the target population

The number of individuals selected for field measurement must be sufficient to make it likely that estimates of population means and sampling errors will be sufficiently accurate and precise to cover the variability within the population of interest).

Where population parameters are estimated from the sum of sub-samples or separate models or relationships, double counting of pools must be avoided. All errors must, as far as possible, be identified, and quantified. These include sampling errors, measurement errors, and model errors.

Effective application of sampling strategies and models often relies on stratification by climate (rainfall, temperature) or broad environmental conditions (altitude, topography, soil type), possibly integrated into bio-geo-climatic zones. Such data may also be used directly to develop growth indices (e.g. net primary productivity) or as input into growth models or for prediction of carbon allocation ratios. Networks of weather stations and historical records can be enhanced through spatial modelling approaches to develop climate surfaces for use as input into models or for more effective stratification.

Permanent plots, can be used to improve the accuracy of change estimation when repeatedly measured over time. However if these plots are treated in a way that is different from the rest of the forest (e.g. not harvested or thinned in the same way), or if the original population changes due to the removal of specific types of land without a corresponding removal of plots, the permanent plot sample will no longer be representative of the current forest. Remotely-sensed data, such as canopy cover or disturbance, may be used to determine whether the permanent plots have been treated in a non-representative fashion. If the permanent plots are no longer representative of the larger forest, then new plots may be required to represent more accurately the current condition. If a subset of the already established plots continues to be representative, these can continue to be used by regarding them as a stratum or strata.

Alternatively, permanent plots may be incorporated into an approach whereby models and remotely sensed auxiliary variables are used to increase precision. Sampling with partial replacement systems where a proportion of plots are replaced each measurement period has been used in the past as a compromise to estimating change and current condition, but have generally been found to be a complex compromise and difficult to maintain.

Appendix C   Country examples – Tier 3 integration

CANADA

Stand-level methods (with empirical forest growth models and dynamic dead organic matter

Canada applies a Tier 3 methodology to estimate emissions and removals from its Forest Land. Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS - Kurz & Apps, 2006) includes the CBM-CFS3 model (Kull et al., 2006; Kurz et al., 2009; Stinson et al., 2011). This model integrates forest inventory and yield curves with spatially-referenced activity data on Forest Management and natural disturbances (fires, insect infestations) to estimate forest carbon stocks, carbon stock changes, carbon dioxide emissions and removals and methane and nitrous oxide emissions.

The CBM-CFS3 is an example of a flexible integration framework that can implement both spatially-referenced and spatially-explicit approaches (both polygon and pixel-based) to simulate forest carbon dynamics. Moreover, the model can simulate a single stand, a region or several hundred million hectares of forests. And depending on available data, it can be scaled up from representing a small number of forest strata to representing many thousands of forest strata. The model has been applied in Canada, 26 European Union countries, Russia, Korea, Mexico, China and other regions. Because the model was developed more than 15 years ago, the main constraints in the toolbox arise from software and hardware limitations that make it difficult and impractical to scale the model to pixel-based approaches with millions of pixels. While some tools have been developed as interim solutions, work is under way to implement the scientific modules of the CBM-CFS3 on a new platform (FLINT).

The CBM-CFS3 model uses regional ecological and climate parameters to simulate carbon transfers among pools, to the forest products sector and to the atmosphere. The CBM-CFS3 model tracks emissions and removals as they actually occur over time. Harvesting and natural disturbance result in significant transfers of dead biomass carbon to the litter and dead organic matter pools. The model simulates the subsequent slow decay of the biomass that results in emissions for years or decades following the harvesting or natural disturbance, depending on the decay rates, as well as the removals that occur as forest stands regenerate after the disturbance.

As a result of this approach, which aims to estimate actual emissions and removals when they occur, the model is able to estimate more accurately the long-term impact of disturbances and provide accurate projections, as is required in the construction of a projected reference level. For further detail, see Chapter 7 and Annex 3.4 of Canada's 2010 and 2011 National Inventory Reports.

Canada's area under forest management (229 million hectares) covers about 66% of the country's forests. The area subject to forest management is defined using an area-based approach as outlined by the IPCC (IPCC 2003) and includes:

▸ lands managed for the sustainable harvest of wood fibre

▸ lands under intensive protection from natural disturbances (e.g., fire suppression to protect forest resources)

▸ protected areas, such as national and provincial parks that are managed to conserve forest ecological values.

Canada's monitoring system draws on the close collaboration among scientists and experts in different disciplines. It was recognized early on that the approaches, methods, tools and data that are available and most suitable for monitoring human activities in one land category are not always appropriate for

another. Important differences exist in the spatial framework specific to each land category, with the risk that activity data and estimates become spatially inconsistent.

In managed forests, the analysis units considered in the development of the inventory are the management units found in provincial and territorial forest inventories. For the purpose of this assessment, managed forests were classified into some 523 analysis units across 12 provinces and territories. Analysis units typically result from the intersection of administrative areas used for timber management and ecological boundaries.

The most suitable spatial framework for GHG estimation on agricultural lands (Cropland category) is the National Soil Database of the Canadian Soil Information System and its underlying soil landscapes. A full array of attributes are used to describe a distinct type of soil and its associated landscapes, such as surface form, slope, typical soil carbon content under native and dominant agricultural land use, and water table depth.

The age-class distribution of the managed forest is captured by the forest inventory data and annual change information (due to harvesting, fire and insect infestations) used in the CBM-CFS3. The managed forest is composed of relatively old stands, with over half being 80 years or older in 2009. This age-class structure reflects past natural disturbances and management.

The input data for the CBM-CFS3 include information about forest growth rates for different forest types, site classes and regions. A description of how growth data by species and region are represented in the model and the source of the information can be found in Canada's 2010 and 2011 National Inventory Reports (Chapter 7 and Annex 3.4), Kurz et al., (2009) and Stinson et al., (2011). The same growth and yield curves are used for both projected removals and for estimates of actual removals.

Canada's managed forest is composed of substantial areas of slow-growing and relatively old stands. Harvesting decisions are determined according to provincial and territorial policies and regulations, taking into account the age of the forest, proximity to processing facilities, environmental considerations and other factors. Based on provincial and territorial input, CBM-CFS3 simulates harvesting at the appropriate age which varies by species and region and can include salvage logging of stands previously disturbed by fire or insects.

The following projected management activities are considered: clear-cut harvesting, selection harvesting, salvage harvesting, shelter wood harvesting, commercial thinning and slash burning. The proportion of the total harvest accounted for by the various harvesting methods is projected using the recent average proportion of harvest to total harvest. The impacts of other silvicultural activities, such as tree planting, fertilization, and pre-commercial thinning are not accounted for explicitly because these activities are rarely implemented (fertilization, pre-commercial thinning) or their impacts are implicitly accounted for in the growth and yield data used in CBM-CFS3.

Canada reports the HWP pool using three categories of (sawnwood; wood panels, paper) and a Tier 2 approach utilising data from the FAO, and country-specific wood density factors. This information is converted to carbon using Tier 2 estimates of emissions from both exported and domestically produced and consumed HWP.

Canada's forest is continental in scale: a forest of this size means that almost every year some portion of the forest is affected by severe natural disturbances (i.e. wildfire and insect infestations). Canada predicts with a high degree of confidence the minimum level of wildfire that will occur every year. The background value of 95,000 hectares of managed forest burned each year is based on data from the past 51 years (1959-2009) which show that at least this amount burned during 90% of the years. The effects of background endemic insect infestations are captured in forest inventory and increment data.

Emissions from the background level of wildfire are calculated using a direct wildfire emissions factor of 0.132 kt CO_2e per hectare burned. This factor is derived from data underlying Canada's 2011 National Inventory Report, and is the average emissions factor for wildfires in the managed forest during 1990-2009. Non-carbon dioxide emissions are substantial, amounting to 19% of the direct fire emissions.

AUSTRALIA

Pixel based methods (with hybrid growth models, dynamic dead organic matter models and agriculture)

The land area of Australia is about 760 million hectares. About 25% of total human induced greenhouse gas emissions in Australia result from activities such as agricultural production and land clearing. Given the size of Australia, it is not economically feasible or logistically practical to measure emissions and removals of greenhouse gases over such a large area with the use of direct emissions estimation methods alone e.g. field sampling. Given these national circumstances, the design of Australia's national inventory system for the land sector relies heavily on the use of a modelling framework, to estimate the carbon stock change in biomass (above and belowground), litter and soil carbon resulting from land use and management activities.

In 1998 Australia embarked on a program to develop a comprehensive system to estimate emissions and removals from Australia's land based sector. The system integrates spatially referenced data with an empirically constrained, mass balance, carbon cycling ecosystem model (FullCAM) (Richards and Evans, 2000; Richards, 2001) to estimate carbon stock changes and greenhouse gas emissions (including all carbon pools, gases, lands and land use activities). FullCAM is an ecosystem model that calculates greenhouse gas emissions and removals in both forest and agricultural lands using a mass balance approach to carbon cycling. As a significant amount of emissions and removals of greenhouse gases occur during transitions between forest and agricultural land use, integration of agricultural and forestry modelling was considered essential. Currently the system supports Tier 3, Approach 3 spatial enumeration of emissions and removals calculations for the following sub-categories:

- ▸ Forest land converted to Cropland

- ▸ Forest land converted to Grassland

- ▸ Grassland converted to Forest land

- ▸ the agricultural system components of Cropland remaining cropland and Grassland remaining grassland.

Australia uses a combination of geographically explicit data to represent land areas, consistent with Approach 2 and 3 as described in IPCC 2006 Guidelines and the 2013 IPCC KP Supplement. Data on areas of forest management for Forest Land remaining Forest Land are drawn from Australia's National Forest Inventory. Supplementary spatial information from the Land Use Mapping programme of Australia's Bureau of Agricultural Resource Economics and Sciences is used to identify land areas in the Cropland remaining Cropland, Grassland remaining Grassland, Wetlands, and Settlements categories.

Spatial enumeration is achieved through the use of a time series (since 1972) of Landsat satellite data which is used to determine change in forest extent. The forest cover change information is used with time series climate data and spatially referenced databases of land management practices. Australia monitors forest cover using national coverages of Landsat satellite data (MSS, TM, and ETM+) across 25 time epochs (periods between dates for which remote sensing data are available) from 1972 to 2016 which have been assembled and analysed for change. These national maps of forest cover are annual from

2004 and are used to detect fine scale changes in forest cover at a 25 m by 25 m resolution. Where forest cover change is identified in an epoch, the actual date of forest cover change in each 25 m by 25 m pixel is randomly allocated within the sequence of satellite pass dates.

FullCAM models both biological and management processes which affect carbon pools and transfers between pools in forest and agricultural systems. The exchanges of carbon, loss and uptake between the terrestrial biological system and the atmosphere are accounted for in the full, closed cycle mass balance model which includes all biomass, litter and soil pools. Analysis and reporting includes all carbon pools (biomass, dead organic matter and soil), greenhouse gases (CO_2, CH_4 and N_2O), and covers both forest and non-forest land uses. It is an integrated suite of the following models:

- A hybrid forest growth and biomass estimation (Brack et al., 2006; Waterworth and Richards, 2008):

  - This uses 3PG - the physiological growth model for forests (Landsberg and Wareing, 1997; Landsberg et al., 2000; Coops et al., 1998; Coops et al., 2000) to develop a site index rather than predict biomass directly

- CAMFor - the carbon accounting model for forests (Richards and Evans, 2000a):

  - This model is based on CO2Fix and allows for the inclusion of management and natural disturbance events

  - It also models dead organic matter pools based on estimates of turnover and decomposition

- CAMAg - the carbon accounting model for cropping and grazing systems (Richards and Evans, 2000b)

  - To account for agriculture, and the effects of management and natural disturbances

  - It also models dead organic matter pools based on estimates of turnover and decomposition

- Roth C - the Rothamsted Soil Carbon Model – Roth C (Jenkinson et al., 1987; Jenkinson et al., 1991).

  - This is applied for all soils.

To meet its objective of providing a comprehensive carbon accounting and projections capacity for land based activities, the National Inventory System (formerly known as the National Carbon Accounting System) has required strategic development of several key datasets and modelling and accounting tools. The system and underlying supporting data and science have been documented in many reports that are publicly available. Early reviews made it clear that approaches based on measurement were not feasible and that the calibration of relevant models would be required. The most significant value of FullCAM is that it allows for an ongoing evolution in the quality of any data inputs, be they for future accounting periods or improvements in fundamental input data or model calibration. Since 2014, FullCAM outputs have been downloaded into a SQL output database providing a ready tool to facilitate transparency, quality control and publication of important variables. Such ongoing improvements were not as readily made under the regional approaches envisaged formerly. FullCAM also provides for greater responsiveness to the various international reporting demands. The fine spatial resolution, activity-driven and time-based modelling provides a capacity to report at both project and continental scales, in response to specific activities, and with sensitivity to the timing of an activity.

References:

Brack, C., Richards, G., & Waterworth, R.M. 2006. Integrated and comprehensive estimation of greenhouse gas emissions from land systems. *Sustainability Science.* 1:1:91-106.

Waterworth, R.M., Richards, G.P., Brack, C.L., & Evans, D.M.W. (2007). A generalised hybrid process-empirical model for predicting plantation forest growth. *Forest Ecology and Management.* 238:231-243.

INDONESIA

Pixel-based (empirical models, emissions factors and Approach 3 time series data)

The Government of Indonesia is committed to ambitious greenhouse gas (GHG) emissions reduction targets. With a significant proportion of Indonesia's total emissions generated by land-based activities, the sector is a major focus of mitigation efforts. Understanding the size and source of historical emissions is critical to planning efficient and effective interventions, as well as gauging the potential impact of alternative land management options on future emissions. This is why the Government of Indonesia has been developing the Indonesian National Carbon Accounting System since 2008, with the first national level, annual results publicly released in December 2015, covering forests and peatlands for the period 2001 to 2012. The results of the system along with all documentation on methods is now available in the INCAS website.

The system uses:

▸ A time-series of forest-non-forest data developed from remote sensing data to determine areas of change (using a time series algorithm)

▸ Maps of forest type based on existing maps

▸ Spatial and non-spatial forest management information

▸ Estimates of area burnt from hotspot mapping and manual mapping

▸ Empirical forest growth models developed from past measurements from Indonesia's National Forest Inventory

▸ Allometric models based on Indonesia specific data

▸ Dynamic modelling of dead organic matter

▸ Tier 2 emissions factors for mineral soils and peat emissions

▸ Tier 1 emissions factors for non-carbon dioxide emissions, in particular from fire.

The data are integrated using a combination of FullCAM in empirical mode (for the forest growth and dead organic matter) and simple excel sheets for Tier 1 and 2 data. The results of these systems are then combined to produce annual GHG emissions and removals estimates for deforestation, forest degradation, sustainable management of forests and enhancement of forest carbon stocks.

The INCAS represents a good example of interagency collaboration, with the Indonesian National Institute of Aeronautics and Space (LAPAN) developing the time series forest/non-forest data, the Directorate General of Forestry Planning and Environmental Management providing forest inventory and forest type maps, with integration managed through the Forest Research, Development and Innovation Agency of the Ministry of Environment and Forestry (FORDA). A core feature of the INCAS has been the development of a small core team of experts within FORDA. Consistent and sustained support for these experts has allowed the system to rapidly develop in recent years and provides a good example of a successful management structure for other countries.

The INCAS is by no means finished. The release of the first national results represents the first step in INCAS development. Planned improvements include potential to move to a new integration tool (such as FLINT), full pixel based analysis for both land use change and fire, and continual progression towards Tier 3 methods for key emissions sources such as peat. Indonesia has also indicated an interest in developing the system to account for the entire land sector in the future.

KENYA

Pixel-based full lands accounting (SLEEK, Kenya)

The System for Land-based Emissions in Kenya (SLEEK) has been under active development since 2013. The system differs from most others as it is attempting to develop emissions estimates for the entire land sector within a single system. In this case reporting for forests and REDD+ becomes a sub-set of the entire system. This has the advantage that all land areas are included as well as the transitions among land categories. Moreover this helps to ensure that REDD+ reporting is consistent with the methods and data used to develop biennial reports and other actions under the INDCs.

Initial runs of the system should be completed in mid 2016, with official runs occurring prior to the end of 2016. The current design uses the following data:

▸ Annual time series of land cover (9 classes) specifically developed by the Department of Remote Sensing of in collaboration with the Kenya Forest Service and Ministry of Agriculture.

▸ Semi-automated attribution data to determine cause of cover change to produce land use maps

▸ Empirical forest growth models derived from forest inventory and research site data

▸ WOFOST model to estimate crop growth

▸ Empirical pasture growth models

▸ Roth C soil carbon model

▸ Climate data

▸ Tier 1 modules where higher tiers have not been calibrated (for example, many soils types) or not available (for example, Wetlands).

These data are integrated within a single framework called the Full Lands Integration Tool (FLINT). SLEEK has led the development of the FLINT as a generic tool (see Table 1: Versions of IPCC guidance) that can be easily applied by other countries. The FLINT framework has also been used to guide the management of the program. This has allowed all the different agencies to work together around a single tool and approach, while still maintaining independence and ownership of their core work.

Several government agencies have come together to help develop SLEEK. This collaboration is a key achievement of the program and has helped prevent duplication of effort. Members from each

organisation are represented on a series of Element Working Groups that help set the direction and plan work to deliver the required products. The organisations include:

▸ Kenya Forest Service, who are developing biomass estimates and forest growth curves and estimates of dead organic matter for plantations and natural forests

▸ Ministry of Agriculture, who are responsible for all soils monitoring and modelling (for all land uses), and for managing the crop growth modelling

▸ Department of Resource Surveys and Remote Sensing (DRSRS), who are leading the land cover mapping program

▸ Regional Centre for Remote Sensing and Mapping, who are supporting DRSRS to develop the time series land cover maps

▸ Kenyan Meteorological service, who are producing daily climate grids for key weather variables to support the models

▸ Kenyatta University and Embu University College, who are developing crop models and conducting field trials.

MEXICO

Pixel-based forest and deforestation accounting (empirical models and Approach 3 time series data; Mexico)

The application of the CBM-CFS3 to regions in Mexico is an on-going collaboration between the forest services of Mexico and Canada. Following the approach selected in Canada, the intersections of administrative (state boundaries) and ecological (terrestrial ecozones, Level 1) were used to define 94 spatial units. The model has been applied in a spatially-referenced Tier 3 approach in six states in Mexico to estimate past and projected future greenhouse gas emissions and removals. The model has also been applied using a spatially-explicit approach to a single Landsat scene in Mexico to demonstrate the approach and to quantify the impacts of four activity data sets derived from remote sensing products, each set with and without attribution of observed land-cover changes to specific disturbance types (Mascorro et al., 2015). The results demonstrate that in a heterogeneous landscape with frequent small-scale disturbances and rapid regrowth, remote sensing products based on 30-meter resolution and annual time steps perform better than products based on 250-meter resolution sensors or products that detect changes over multi-year periods (Mascorro et al., 2015; Kurz et al., 2015).

Analyses of past emissions and projections of future REDD+ scenarios for the entire Yucatan Peninsula in Mexico were based on land-cover change matrices developed from remote sensing products and time-series of change maps developed by Mexican agencies. The CBM-CFS3 was then applied to estimate past GHG emissions and removals as affected by human and natural disturbances. Future projections were implemented with business-as-usual disturbance rates (averages of the past 10 years) and alternative scenarios of reduced rates of deforestation and degradation (Kurz et al., 2015). One of the lessons learned in the application of the CBM-CFS3 in Mexico is that data on fire wood collection, a potentially important human impact on biomass and dead organic matter carbon stocks in forest ecosystems, are very difficult to obtain.

Appendix D Use of global forest change map data

Case Study - Guyana

Motivation

Many tropical countries like Guyana are interested in establishing whether the UMD Global Forest Change products provide a useful and reliable source of information that can be used or adapted to satisfy reporting requirements, particularly for REDD+ or other programs that involve results-based payment for the avoidance of deforestation. Of particular interest to Guyana are the freely available Global Forest Maps provided by the UMD for estimating annual forest gains and losses. The Guyana Forestry Commission is interested in the value of these data in the context of REDD+ and specifically how statistics from the global products relate to gross deforestation.

Technique

Guyana undertook a careful assessment of the accuracy of the UMD Global maps by comparing these data with maps produced by its own MRV system, and with independent reference data. Global Forest Change Maps 2010-2104 were provided by the UMD (Hansen et al., 2013) and compared with the Guyana Forestry Commission's forest change maps (MRV) which are based on careful interpretation of nationwide satellite image coverage. The Guyana MRV system had used 30m-Landsat TM and ETM + imagery for the five epochs: 1990, 2000, 2005, 2009 and 2010. For 2011, 2012, 2013 and 2014 the Guyana MRV system used 6.5m-RapidEye imagery. In accordance with the Marrakesh Accords (UNFCCC, 2001), Guyana has elected to classify land as forest if it meets the criteria of minimum tree cover of 30%, a minimum tree canopy height of 5 m and a minimum area of 1 ha. The forest area was mapped by the Guyana Forestry Commission by excluding non-forest land cover types, such as water bodies, infrastructure, mining and non-forest vegetation. The non-forest land cover types are classified into six broad land use categories in accordance with IPCC reporting guidelines.

The UMD Global Forest Change data provides an estimate of tree cover percentage for each 30m-Landsat pixel (Hansen et al., 2013). The first step is to identify the percentage cover value in the UMD Global product that best corresponds to actual forest cover in Guyana.

The second step is to analyse the forest change (loss/gain) in the global data product and compare that with Guyana's annual forest loss maps from the MRV system for the whole country.

The third assessment uses independent high quality reference data to assess the accuracy of both the UMD Global Forest Change and the Guyana MRV system data based on a two-stage stratified random sampling design with 143 (5 km by 15 km) first stage samples. The reference data consisted of 0.25 m aerial imagery and some independent reinterpretation of 6.5 m RapidEye scenes.

Results

Figure 1 (a) shows Guyana's non-forest area as a percentage plotted against the different tree cover percentage thresholds in the UMD Global Forest Change product. The result indicates that a threshold tree cover percentage of 90% provides the closest correspondence Guyana non-forest area as at 2000. This analysis shows that a user should not assume that forest definitions on the ground correspond well with the percentage canopy cover reported by the algorithm used in the global forest cover product. Using Guyana's forest definition (30% canopy cover) results in an underestimation of non-forest and an overestimation of forest land cover (see Figure 1a).

Figure 1(b) shows estimates of annual forest loss from the UMD Global product and Guyana's MRV system for years 2010 to 2014 inclusive. For years 2010 and 2011 Landsat data were used by both Guyana MRV system and UMD Global product to assess change. Comparatively the estimates of forest loss look broadly similar. For years 2012, 2013 and 2014 the UMD global product appears to underestimate forest loss when compared with the Guyana MRV system data. Over this period Guyana switched to the interpretation of 6.5 m RapidEye imagery.

Figure 15: Comparison of UMD global map and Guyana maps

Accuracy assessment

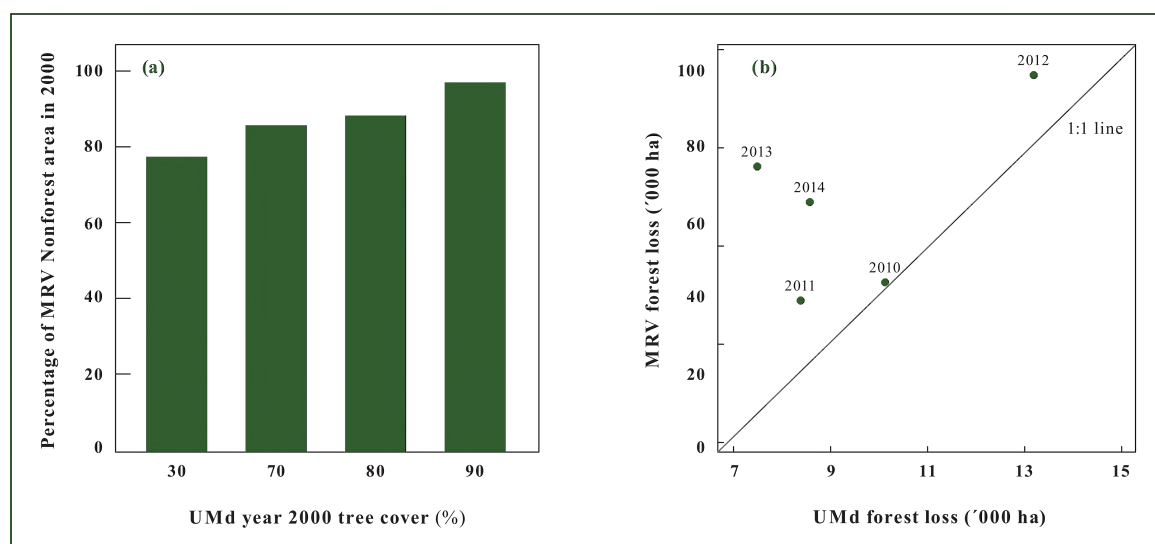The results of an analysis of mapping accuracy are shown in Table 21: Error matrix between UMD global product and Guyana maps and reference data. The analysis is based on a probability-based sample that uses an independent reference data to assess accuracy of both the UMD global forest change data and the Guyana MRV system data.

The UMD data gives a User's accuracy of 94% and a Producer's accuracy of 73%. This compares less favourably than the user's and producer's accuracies of 80% or better reported by Hansen et al., (2013) per climate domain and for the globe as a whole. The equivalent User's and Producer's accuracies for the Guyana MRV system data are 99% and 99.9% showing, as expected, that a deforestation estimate derived from the interpretation of high spatial resolution data is more accurate (Table 21: Error matrix between UMD global product and Guyana maps and reference data) than a global map product.

Table 21: Error matrix between UMD global product and Guyana maps and reference data

Error matrix		Reference data			
		Forest	Non forest	Total	User accuracy
Maryland map	**Forest**	50751	1127	51878	97.8%
	Non forest	198	3043	3241	93.9%
Total		50949	4170	55119	
Producer accuracy		99.6%	72.9%		97.6%

MRV map	Forest	50921	6	50927	99.9%
	Non forest	28	4164	4192	99.3%
Total		50949	4170	55119	
Producer accuracy		99.9%	99.9%		99.9%

Discussion

Overall the UMD Global forest map products are easily accessed and provide a rapid spatial overview of forest area and forest change patterns across Guyana. When taken over the 14 years (2001-2014) of available data, the national-scale statistics for forest area and forest change match well with Guyana's MRV system.

The ability of the UMD Global products to provide indicative maps of loss and gain is useful as it indicates where change occurs. Even if change is due to natural processes it is valuable to be able to visualise change on a year on year basis as shown in Figure 2.

There are however, some limitations. This is observed in Figure 2 which compares the area of annual change from the UMD Global product against Guyana MRV system mapped from RapidEye. It is clear that for any one year the Maryland global data does not capture all of the change. In essence this means the UMD Global product could not be relied upon to provide an accurate annual loss / gain or rate of change statistic.

This is to be expected and is one of the reasons that the MGD advocates the use of reference data to adjust for mapping errors when quantitative estimates of forest area or rates of change are required.

For Guyana, the UMD forest change maps underrepresent the patterns of gross deforestation in comparison with reference data. In recent years the greatest amount of forest loss has been associated with alluvial gold mining and mining roads and other infrastructure. In this regard the pixel size of Landsat is too large to capture small area change such as ribbon-mining infrastructure (Figure 2).

The inability to distinguish between anthropogenic loss (deforestation) and loss from natural processes is a limitation in the context of REDD+ where the causes of change is important in assigning emission/ removal factors to activity data.

Figure 16: Illustration of forest area in Guyana
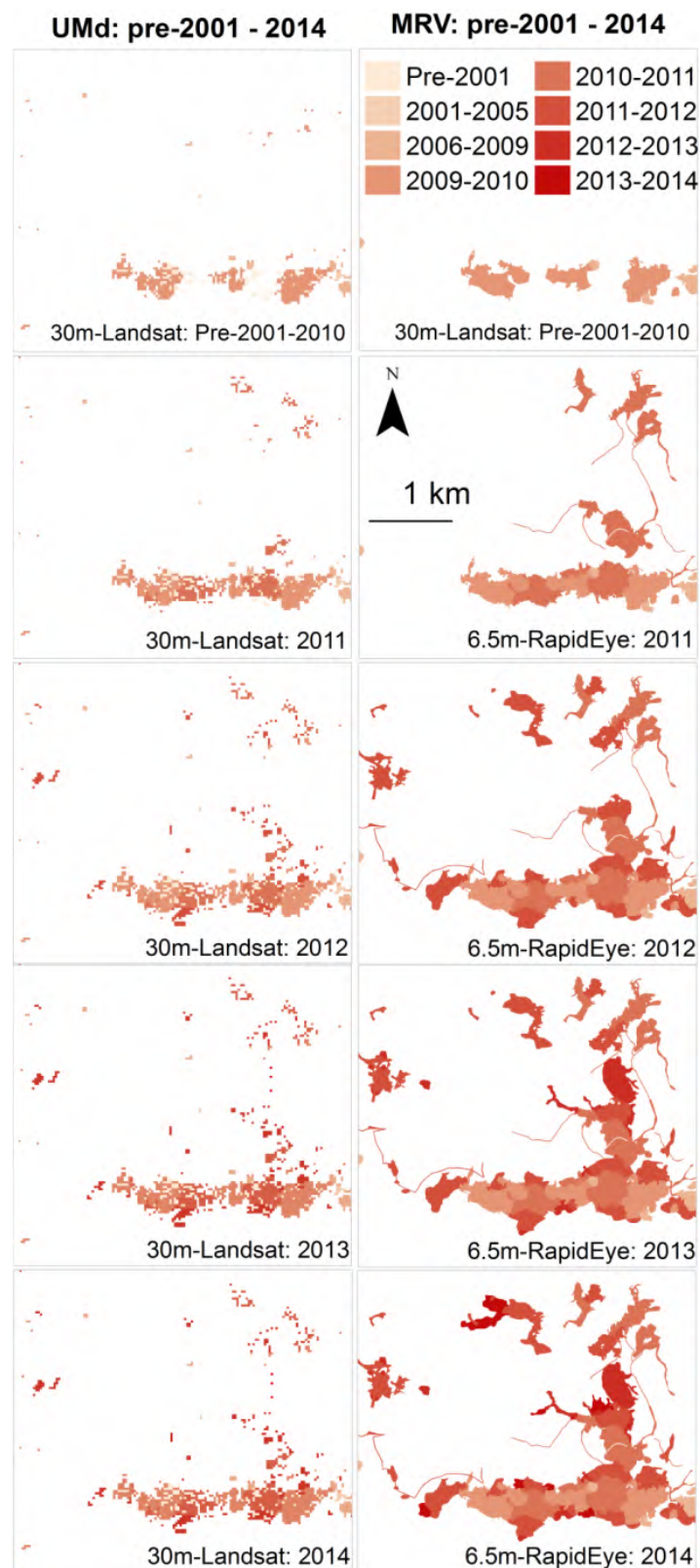
Forest loss has been mapped in the UMD Global product (left) and MRV system (right) maps between pre-2001 and 2014

In the context of REDD+, activity data may be associated with particular definitions. The UMD Global data does not take into account forest definitions such as areas more or less than a hectare. For example shifting cultivation and other types of forest degradation that appear as forest loss are mapped as deforestation in the UMD Global map. This results in an overestimation in forest change and carbon emissions from deforestation. Further country-specific definitions that operate below the minimum mapping unit of 1 ha may further limit the utility of UMD Global map product.

For Guyana there are areas that suffer from persistent cloud cover and that appears to be reflected in the UMD Global product for some parts of the country, especially along the Caribbean coastline. It is difficult to know how many Landsat scenes have been used for the change (loss/gain) detection and precisely from which time period these scenes are taken. Again, this limits the use of the UMD global products in annual REDD+ activity data monitoring.

References

Guyana MRV Report Year 4.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., & Townshend, J.R.G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*. 342:850–853. Data is available online.

UNFCCC. (2001). Report of the Conference of the Parties on its Seventh Session. United Nations Framework Convention on Climate Change (UNFCCC). 29 October – 10 November 2001. UN Doc. FCCC/CP/2001/13 (2002). Marrakesh. 69p.

Appendix E   Relative efficiencies

This appendix contains the results and the literature references supporting the conclusions summarized in the dot points in Box 19: Relative efficiency.

Table 22: Relative efficiency of using the national versus UMD GFC based F/NF and change maps for Gabon

Country: Gabon				
Type of reference data: independent interpretation of satellite imagery				
Type of map/remotely sensed data	**Biome/type of forest**	**Target variable**	**Relative efficiency of using national vs global map**	**% reduction in sample size**
UMD GFC tree cover with 30% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Forest area	9.5	89.4
UMD GFC tree cover with 30% cover threshold F/NF no MMU map	Tropical rainforest	Forest area	9.2	89.1
UMD GFC tree cover with 70% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Forest area	3.8	73.6
UMD GFC tree cover with 70% cover threshold F/NF no MMU map	Tropical rainforest	Forest area	3.8	73.8
UMD GFC tree cover with 30% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Net forest change area	2.0	49.7
UMD GFC tree cover with 30% cover threshold F/NF no MMU map	Tropical rainforest	Net forest change area	2.6	61.0
UMD GFC tree cover with 70% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Net forest change area	4.6	78.3
UMD GFC tree cover with 70% cover threshold F/NF no MMU map	Tropical rainforest	Net forest change area	2.6	61.6
Reference:				
Sannier, C., McRoberts, R. E., & Fichet, L. (2016). Suitability of Global Forest Change data to report forest cover estimates at national level in Gabon. *Remote Sensing of Environment*. 173:326–338.				

Table 23: Relative efficiency of using the national and UMD GFC based F/NF and change maps against sample data for Gabon

Country: Gabon				
Type of reference data: independent interpretation of satellite imagery				
Type of map/remotely sensed data	Biome/type of forest	Target variable	Relative efficiency of using map	% reduction in sample size
National F/NF Map	Tropical rainforest	Forest area	57.7	98
UMD GFC tree cover with 30% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Forest area	6.1	83.6
UMD GFC tree cover with 30% cover threshold F/NF no MMU map	Tropical rainforest	Forest area	6.3	84.0
UMD GFC tree cover with 70% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Forest area	15.3	93.4
UMD GFC tree cover with 70% cover threshold F/NF no MMU map	Tropical rainforest	Forest area	15.1	93.4
National F/NF Map	Tropical rainforest	Net forest change area	2.66	62.4
National F/NF Map	Tropical rainforest	Net forest change area	1.12	10.9
UMD GFC tree cover with 30% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Net forest change area	0.57	n/a
UMD GFC tree cover with 30% cover threshold F/NF no MMU map	Tropical rainforest	Net forest change area	0.44	n/a
UMD GFC tree cover with 70% cover threshold F/NF 1 ha MMU map	Tropical rainforest	Net forest change area	0.24	n/a
UMD GFC tree cover with 70% cover threshold F/NF no MMU map	Tropical rainforest	Net forest change area	0.43	n/a

Country: Gabon				
Type of reference data: independent interpretation of satellite imagery				
Type of map/remotely sensed data	**Biome/type of forest**	**Target variable**	**Relative efficiency of using map**	**% reduction in sample size**
Reference: Sannier, C., McRoberts, R. E., & Fichet, L. (2016). Suitability of Global Forest Change data to report forest cover estimates at national level in Gabon. *Remote Sensing of Environment*. 173:326–338. Desclée, B., Mayaux, P., Hansen, M., Lola Amani, P., Sannier, C. Mertens, B., Haüsler T., Ngamabou Siwe, R., Poilvé, H., Gond, V., Rahm,M., Haarpainter, J., Kibambe Lubamba, J.P. (2014) Evolution of forest cover area at a national and regional scale and drivers of change in The forests of the Congo basin—State of the forest 2013. Eds : deWasseige C., Flynn J., LouppeD., Hiol Hiol F.,Mayaux Ph. – 2014.Weyrich. Belgium. 328 p.				

Table 24: Relative efficiency of using the national and UMD GFC based F/NF against sample data for Tanzania

Country: Tanzania				
Type of reference data: National inventory of ground plots (first 6 cases; photo interpretation of visual images (cases 7 and 8)				
Type of map/remotely sensed data	**Biome/type of forest**	**Target variable**	**Relative efficiency of using map**	**% reduction in sample size**
UMD global map (tree cover and Landsat digital numbers from mosaics). Calibrated to local forest definition.	Miombo woodlands	Forest area	1.4	29%
UMD global map. Tree cover with 10% cover threshold.	Miombo woodlands	Forest area	1.0	0%
UMD global map. Tree cover with 20% cover threshold.	Miombo woodlands	Forest area	1.2	17%
Global ALOS PALSAR forest/non forest map. Calibrated to local forest definition.	Miombo woodlands	Forest area	1.7	41%
Global ALOS PALSAR forest/non forest map.	Miombo woodlands	Forest area	1.5	33%
RapidEye optical satellite images. Calibrated to local forest definition.	Miombo woodlands	Forest area	2.0	50%
UMD global map (tree cover). Calibrated to local forest definition.	Miombo woodlands	Forest area	1.8	44%

Country: Tanzania

Type of reference data: National inventory of ground plots (first 6 cases; photo interpretation of visual images (cases 7 and 8)

Type of map/remotely sensed data	Biome/type of forest	Target variable	Relative efficiency of using map	% reduction in sample size
RapidEye optical satellite images. Calibrated to local forest definition.	Miombo woodlands	Forest area	1.7	41%

Reference:

Næsset, E., Ørka, H.O., Solberg, S., Bollandsås, O.M., Hansen, E.H., Mauya, E., Zahabu, E., Malimbwi, R., Chamuya, N., Olsson, H. & Gobakken, T. 2016. Mapping and estimating forest area and aboveground biomass in miombo woodlands in Tanzania using data from airborne laser scanning, TanDEM-X, RapidEye, and global forest maps as auxiliary information: A comparison of estimated precision. Remote Sensing of Environment, 175: 282-306. Ørka, H.O. 2015. Accuracy assessment of global forest maps and high-resolution satellite imagery for forest area estimation in a first phase of MRV for REDD+. Report to the Norwegian Space Centre, 29 June 2015, unpublished, 19 pp.

Appendix F   Developing and using allometric models to estimate biomass

Introduction

Within a specified forest stratum biomass carbon can be estimated using ground-based methods entailing an inventory of stem diameters and/or heights, and application of allometric models which relate above- and below-ground biomass to the inventory measurements. For a detailed treatment of important issues see Picard et al., (2012) and Chave et al., (2004). Stratification is a critical step in defining the appropriate domain in which an allometric model is developed and applied.

Allometric models for estimation of biomass have most commonly used stem diameter as the explanatory variable, with some also using tree heights, and to a lesser extent, canopy width and wood density. A growing number of researchers have shown that stem diameter can be an adequate biomass predictor at local or regional scales, with height or wood density, providing little improvement in the efficiency of allometric predictions of above-ground or below-ground biomass (e.g. Brown et al., 1989; Ketterings et al., 2001; Jenkins et al., 2003; Chave et al., 2005; Basuki et al., 2009; Xiang et al., 2011: Paul et al., 2014). This suggests that stem diameter accounts for common geometric, biomechanical and hydrodynamic principles that govern the transport of essential materials in trees (West et al., 1999; Enquist and Niklas, 2001). However, in some tropical forests, height and wood density have been shown to be important variables and their explanatory power should therefore be examined (e.g. Chave, 2005; Feldpausch et al., 2011 and 2012; Chave et al., 2014). Feldpausch et al., (2011 and 2012) showed that inclusion of tree height as an allometric factor can reduce error in estimates of tropical biomass and hence carbon stocks and emissions due to deforestation. Height at which diameters are measured often varies between forests based on the heights of the trees, shape of the stem and the average height at which they branch into multiple stems. As a general rule, when establishing an allometric model, the diameters should be measured at 130 cm height, or as high as possible but below the height at which the stem becomes multi-stemmed. This decreases measurement errors. Generally for shrub species, diameters can be measured at 10 cm height. When using an allometric model, trees should be measured at a height consistent with the data used to establish it.

Number of trees to harvest (sample) for deriving allometric models

Sampling error may be significant when selecting trees or shrubs for harvest to develop allometric models. In a global review of the use of allometrics based on stem diameter to determine the biomass of different tree species, Zapata-Cuartas et al., (2012) found that there was an exponential improvement in the precision in predictions of tree biomass with increasing sample size. Similar results were obtained by Roxburgh et al., (2015) who analysed above-ground biomass data from 23 species to quantify sampling errors associated with the development of allometrics. They found marked variability between allometrics in the number of individuals required to satisfy a given level of precision, with a range of 17-95 individuals to achieve biomass estimates with a standard deviation within 5% of the mean for the best performing stem diameter selection algorithm, and 25-166 individuals for the poorest. This variability arises from (a) uncertainty in the relationship between diameter and biomass across allometrics, and (b) differences between the diameter size-class distribution of individuals used to construct an allometric, and the diameter size-class distribution of the population to which the allometric is applied. For pan-tropical forests Chave et al., (2004) found an exponential decline in %CV with increased sample size, with %CV increasing above 10% when 20 trees or fewer were sampled.

Correcting for moisture content

Total above- or below-ground biomass is weighed fresh in the field. Sub-samples are used to determine the dry-weight equivalent. These need to be representative, so as to reduce errors in estimation of dry weight. Ideally, this sub-sampling would be based on each tree component (foliage, bark, twigs, large branches and stems etc.). As a minimum, selected trees should be divided into crown (all foliage and twigs less than about 5 mm diameter) and the remaining bole (stem and branches). The fresh weights of these two components are measured in the field, and then sub-samples (at least three of about 2-3 kg) taken of each component, weighed and transported back to the laboratory and dried (at 70°C) until the dry weights stabilise. For the bole samples, this could take several weeks. Using the average moisture content of sub-samples of each component, a weighted average whole-tree moisture content can be determined based on the relative contribution to total fresh weight of the individual components. For shrubs with no pronounced stem, a separate bole component is not required.

Recent work (Ximenes et al., 2006; Paul et al., 2014) in temperate forests showed moisture content varies more between sites than between species within sites. Within a site, there is evidence that moisture contents varied between growth-habits (e.g. trees compared to shrubs), but within a growth-habit at a given site, variability was just as high within as between species (Paul et al. 2014). Therefore, species-specific moisture content determinations appear to be unnecessary. Rather, average moisture contents can be derived for key genera and growth-habits within sites. Data are limited for tropical forests, so further testing should be conducted.

Selecting the form of an allometric model

The traditional power law allometric model is a simple power function. The linear equivalent of such a power functions is: $\ln(y) = a + b \times \ln(x)$, where y is the dependent variable (biomass, kg DM tree^{-1}), x is the independent variable (stem diameter, cm), a is the intercept coefficient, and b is the scaling exponent. Parameters a and b are estimated using least squares regression.

The logarithmic transformation, in addition to linearizing the relationship, also corrects for heteroscedasticity. Regressions such as these produce unbiased estimates of log-biomass. However direct transformation back to the original scale will yield biased estimates of biomass. There are a number of alternative ways of calculating a bias correction. A common method is to multiply estimates by a correction factor based on the ratio of arithmetic sample mean and mean of the back-transformed predicted values from the regression as described by Snowdon (1991).

There is some evidence that power-law models fail for very large trees, with over-estimates of biomass being common when DBH is >50 cm (Niklas, 1995, Chambers et al., 2001; Chave et al., 2005; Fatemi et al., 2011) due to greater damage, decay and senescence as trees mature. In such cases, non-linear models, or weighted-combined models, should be explored as an alternative to traditional power-law allometric models, with additional explanatory variables such as tree height being included (Brown et al., 1989; Parresol 1999; Bi et al., 2004; Ketterings et al., 2001).

Performance of allometric models

To evaluate model efficiency of allometric models, statistics used are based on those recommended in a review by Parresol (1999), the most important being the Fit Index, otherwise known as model efficiency (Soares et al., 1995). Efficiencies of >0.70 are regarded as reasonable predictors of biomass, but ideally the efficiency should be > 0.9.

Model EF is related to the ratio of the total sum of squares to the residuals sum of squares.

Equation 47

$$EF = 1 - \frac{\sum (O_i - P_i)^2}{\sum (O_i - \bar{O})^2}$$

where O_i are the observed values, P_i are the predicted values, and $\bar{O}$ is the mean of the observed data. A positive value indicates that the simulated values describe the trend in the measured data better than the mean of the observations, with a value of 1 indicating a perfect fit. A negative value indicates that the simulated values describe the data less well than a mean of the observations. The percentage coefficient of variation (CV) can also calculated for each model fit.

Equation 48

$$CV = \frac{SE}{\bar{O}} \times 100$$

where

Equation 49

$$SE = \sqrt{\frac{\sum (O_i - P_i)^2}{N - p}}$$

and N is the number of observations, and p is the number of parameters used in the model.

Generalised (generic) allometric models

For native forests which may contain many different species, it is impractical to develop allometric models for each species at each monitoring site. Generic allometric models may be derived using biomass data from a given species, or growth-habit, across a number of different sites within a specified region, or domain.

Appropriate domain of generic allometric models

Recent studies in woodlands (Williams et al., 2005), eucalypt forests (Montague et al., 2005) and mixed-species plantings (Paul et al., 2013) have shown that although site-species differences were significant, the amount of variation accounted for by these site-species factors was small, thereby supporting the use of generalised allometrics which had slightly less accuracy, but much greater certainty. Several authors have proposed such generalised allometric models for large-scale application for a range of tree or shrub species (e.g. Pastor et al., 1984 (north-east USA); Zianis and Mencuccini 2003 (northern Greece); Jenkins et al., 2003 (USA); Williams et al., 2005 (northern Australia); Montagu et al., 2005 (eastern Australia); Muukkonen 2007 (Europe); Dietze et al., 2008 (south-eastern USA); Xiang et al., 2011 (China); Vieilledent et al., 2012 (Madagascar); Kuyah et al., 2012a (Kenya)).

Generic allometric models should not be applied outside their appropriate domain, given that significant variations in factors such as topography, hydrology and soil nutrient availability may result in systematic biases (Clark & Clark, 2000; Clark, 2005). For this reason, generalised allometrics which have entailed the use of larger pan-continental datasets (Cannell 1984; Brown et al., 1989; Brown, 1997; Chave et al., 2005; Zapata-Cuartas et al., 2012) need to be applied with caution. Verification at fine-scale of these

pan-continental generalised allometrics have often failed (e.g. Basuki et al., 2009; Vieilledent et al., 2012). Madgwick et al., (1991) found that for the eucalypt genera, allometrics developed in one country may not be accurate for the same life-forms growing in other countries.

In order to avoid serious error and bias, the allometric model should not be applied to trees (or other vegetation) outside of the diameter range of the samples used to construct the allometric model.

Categorisation (species versus growth-habit) of generic allometric models

There is clear evidence that above-ground biomass allometry of shrubs differs greatly from that of trees (Keith et al., 2000; Bi, et al., 2004; Paul et al., 2013). Differences in allometry are less significant within these growth-habit categories. Recently, Paul et al., (2016) showed that cost effective prediction of biomass across a wide range of stands in Australia is possible using generic allometric models based on only five plant functional types. In addition to species and life-form, climate is also an important factor influencing allometric models for above-ground biomass. Mean annual rainfall can be a major factor (Brown et al., 1989; Sternberg and Shoshany, 2001; Drake et al., 2003; Chave et al., 2005; De Walt and Chave, 2004).

Development of allometrics for below-ground biomass has generally entailed development of generic rather than site-and-species specific relationships due to limited available data on root biomass (Barton and Montagu, 2006; Ouimet et al., 2008; Peichl and Arain, 2007; Xiang et al., 2011; Paul et al., 2014).

Testing of allometric models

Allometric models should always be tested by comparing with direct measurements of above- and below-ground biomass across the domain region of interest. Examples include: northern hardwood forests in New Hampshire, USA (Arthur et al., 2001), mixed-species found within the Sonoran Desert (Búquez and Martínex-Yrízar, 2011), pure stands of Poplar or Norway Spruce (Pérez-Cruzado et al., 2015) and mixed-species plantings across Australia (Paul et al., 2014).

For direct measurement of above-ground biomass, either a sample of individual trees encompassing the full range of sizes found in the forest in which the allometric is to be applied, or whole plots of about 20m x 20 m (but probably larger in rainforest) are harvested and weighed. Within these plots, sub-plots are selected for root excavation. In forests where stocking is too low (<500 stems/ha) to make whole plot root excavation efficient, roots are excavated around individual trees or shrubs with excavation boundary varied according to the size and distance to neighbouring trees (Picard et al., 2012). Required depth of excavation depends on the depth of tap roots. Previous work suggests that 2 m depth is sufficient (Mokany et al., 2006; Paul et al., 2013). Schenk and Jackson (2002) concluded that globally 50% of all roots are within the upper 0.3 m while 95% of all roots are within the upper 2 m of the soil profile. The majority of root mass is in the coarse (> 2mm) fraction, so that roots finer than this can be ignored where the objective is to measure total tree biomass.

References

Arthur, M.A., Hamburg, S.P., & Siccama, T.G. (2001). The accuracy of allometric estimates of aboveground living biomass and nutrient contents of a northern hardwood forest. *Canadian Journal of Forest Research*. 31:11–17.

Barton, C.V.M. & Montagu, K.D. (2006). Effect of spacing and water availability on root:shoot ratio in Eucalyptus camaldulensis. *Forest Ecology and Management*. 221:52-62.

Basuki, T.M., van Laake, P.E. Skidmore, A.K. & Hussin, Y.A. (2009). Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *Forest Ecology and Management*. 257:1684–1694.

Bi, H., Turner, J., & Lambert, M.J. (2004). Additive biomass equations for native eucalypt forest trees of temperate Australia. *Trees*. 18:467–479.

Brown, S. (1997). Estimating Biomass and Biomass Change of Tropical Forests: A Primer. FAO, Rome.

Brown, S., Gillespie, A.J.R., & Lugo, A.E. (1989). Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science*. 35:881–902.

Clark, D.B., Clark, D.A. (2000). Landscape-scale variation in forest structure and biomass in a tropical rain forest. *Forest Ecology and Management*. 137:185-198.

Clark, J.S. (2005). Why environmental scientists are becoming Bayesians. *Ecology Letters*. 8:2–14.

Cannell, M.G.R. (1984). Woody biomass of forest stands. *Forest Ecology and Management*. 8:299-312.

Chambers, J.Q., Santos, J., Riberio, R.J., & Higuchi, N. (2001). Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. *Forest Ecology and Management*. 152:73-84.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., & Perez, R. (2004). Error propogation and scaling for tropical forest biomass estimates. *Philosophical. Transactions B. Royal Society London.* 359:409–420.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., & Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia.* 145:78–99.

Chave, J., Rejou-Mechain, M., Burquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B. & Vielledent, G. (2014). Improved allometric models to estimate the above-ground biomass of tropical trees. *Global Change Biology.* 20:3177-3190.

De Walt, S.J., & Chave, J. (2004). Structure and biomass of four lowland neotropical forests. *Biotropica.* 36:7–19.

Dietze, M.C., Wolosin, M.S., Clark, J.S. (2008). Capturing diversity and interspecific variability in allometries: A hierarchical approach. *Forest Ecology and Management*. 256:1939–1948.

Drake, J.B., Knox, R.G., Dubayah, R.O., Clark, D.B., Condit, R., Blair, B., & Hofton, M. (2003). Above-ground biomass estimation in closed canopy Neotropical forest using LiDAR remote sensing: factors affecting the generality of relationships. *Global Ecology and Biogeography*. 12:147-159.

Fatemi, F.R., Yanai, R.D., Hamburg, S.P., Vadeboncoeur, H.A., Arthur, M.A., Briggs, R.D., & Levine, C.R. (2011). Allometric equations for young northern hardwoods: the importance of age-specific equations for estimating aboveground biomass. *Canadian Journal of Forest Research*. 41:881–891.

Feldpausch, T.R., Banin, L., Phillips, O.L., Baker, T.R., Lewis, S.L., Quesada1, C.A., Affum-Baffoe, K., Arets, E.J.M.M., Berry, N.J., Bird, M., Brondizio, E.S., de Camargo, P., Chave, J., Djagbletey, G., Domingues, T.F., Drescher, M., Fearnside, P.M., França, M.B., Fyllas, N.M., Lopez-Gonzalez1, G., Hladik, A., Higuchi, N., Hunter, M.O., Iida1, Y., Salim, K.A., Kassim, A.R., Keller, M., Kemp, J., King, D.A., Lovett, J.C., Marimon, B.S., Marimon-Junior, B.H., Lenza, E., Marshall, A.R., Metcalfe, D.J.,

Mitchard, E.T.A, Moran, E.F., Nelson, B.W., Nilus, R., Nogueira, E.M., Palace, M., Patiño, S., Peh1, K.S.-H., Raventos, M.T., Reitsma, J.M., Saiz, G., Schrodt, F., Sonké, B., Taedoumg, H.E., Tan, S., White, L., Wöll, H., & Lloyd, J. (2011). Height-diameter allometry of tropical forest trees. *Biogeosciences*. 8(5):1081-1106.

Feldpausch, T.R., Lloyd, J., Feldpausch, T.R., Lloyd, J., Lewis, S.L., Brienen, R.J.W., Gloor, M., Monteagudo Mendoza, A., Lopez-Gonzalez, G., Banin, L., Abu Salim, K., Affum-Baffoe, K., Alexiades, M., Almeida, S., Amaral, I., Andrade, A., Aragao˜, L.E.O.C., Araujo Murakami, A., Arets, E.J.M.M., Arroyo, L., Aymard G.A., Baker, T.R., Banki , O.S., Berry, N.J., Cardozo, N., Chave, J., Comiskey, J.A., Alvarez, E., de Oliveira, A., Di Fiore, A., Djagbletey, G., Domingues, T.F., Erwin, T.L., Fearnside, P.M., Franc, M.B., Freitas, M.A., Higuchi1, N., Honorio E., Iida, Y., Jimenez, E., Kassim, A.R., Killeen, T.J., Laurance, W.F., Lovett, J.C., Malhi, Y., Marimon, B.S., Marimon-Junior, B.H., Lenza, E., Marshall, A.R., Mendoza, C., Metcalfe, D.J., Mitchard, E.T.A, Neill, D.A., Nelson, B.W., Nilus, R., Nogueira, E.M., Parada, A., Peh, K.S.-H., Pena Cruz, A., Penuela, M.C., Pitman, N.C.A., Prieto, A., Quesada, C.A., Ram´ırez, F., Ram´ırez-Angulo, H., Reitsma, J.M., Rudas, A., Saiz, G., Salomao˜, R.P., Schwarz1, M., Silva, N., Silva-Espejo, J.E., Silveira, M., Sonké, B., Stropp, J., Taedoumg, H.E., Tan, S., ter Steege, H., Terborgh, J., Torello-Raventos, M., van der Heijden, G.M.F., Vasquez, R., Vilanova, E., Vos, V.A., White, L., Willcock, S., Wöll, H., & Phillips, O.L. (2012). Tree height integrated into pantropical forest biomass estimates. *Biogeosciences*. 9(8):3381-3403.

Enquist, B., & Niklas, K. (2001). Invariant scaling relations across tree-dominated communities. *Nature*. 410:655–660.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., & Birdsey, R.A. (2003). National-Scale Biomass Estimators for United States Tree Species. *Forest Science*. 49:12-35.

Keith, H., Barrett, D., & Keenan, R. (2000). Review of allometric relationships for estimating woody biomass for NSW, ACT, Victoria, Tasmania and SA. National Carbon Accounting System Technical Report No. 5b, Australian Greenhouse Office, Canberra, p. 111.

Ketterings, Q., Coe, R., van Noordwijk, M., Ambagau, Y., & Palm, C.A. (2001). Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *Forest Ecology and Management*. 146:119-209.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R., & Neufeldt, H. (2012). Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. *Agriculture, Ecosystems and Environment*. 158:216– 224

Mokany, K., Raison, R.J., & Prokushkin, A.S. (2006). Critical analysis of root:shoot ratios in terrestrial biomes. *Global Change Biology*. 12:84–96.

Montagu, K.D., Dűttmer K., Barton, C.V.M., & Cowie, A.L. (2005). Developing general allometric relationship for regional estimates of carbon sequestration—an example using Eucalyptus pilularis from seven contrasting sites. *Forest Ecology and Management*. 204:113–127.

Muukkonen, P. (2007). Generalized allometric volume and biomass equations for some tree species in Europe. *European Journal of Forest Research*. 126:157–166

Nikilas, K.J. (1995). Size-dependent allometry of tree height, diameter and trunk-taper. *Annals of Botany*. 75:217–227.

Ouimet, R., Camiré, C., Brazeau, M., & Moore, J.D. (2008). Estimation of coarse root biomass and nutrient content for sugar maple, jack pine, and black spruce using stem diameter at breast height. *Canadian Journal of Forest Research.* 38:92–100.

Picard N., Saint-André L., & Henry M. (2012). Manual for building tree volume and biomass allometric equations: from field measurement to prediction. Food and Agricultural Organization of the United Nations, Rome, and Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Montpellier, 215 pp.

Parresol, B.R. (1999). Assessing tree and stand biomass: A review with examples and critical comparisons. *Forest Science*. 45:573-593

Pastor, J., Aber, J.D. & Melillo, J.M. (1984). Biomass prediction using generalized allometric regressions for some northeast tree species. *Forest Ecology and Management*. 7:265-274.

Paul, K.I., Roxburgh, S.H., Ritson, P., Brooksbank, K., England, J.R., Larmour, J.S., Raison, R.J., Peck, A., Wildy, D., Sudmeyer, R., Giles, R., Carter, J.L., Bennett, R., Mendham, D.S., Huxtable, D. & Bartle, J.R. (2013). Testing allometric equations for prediction of above-ground biomass of mallee eucalypts in southern Australia. Forest Ecology and Management.

Paul, K.I., Roxburgh, S.H., England, J.R., Ritson, P., Hobbs, T., Brooksbank, K., Raison, J.R., Larmour, J.S., Murphy, S., Norris, J., Neumann, C., Lewis, T., Jonson, J., Carter, J.L., McArthur, G., Barton, C., Rose, B. (2013). Developing and testing of allometric equations for estimating above-ground biomass of mixed-species environmental plantings. *Forest Ecology and Management.* 310:483-494.

Paul, K., Roxburgh, S., Raison, R.J., Larmour, J., England, J., Murphy, S., Norris, J., Ritson, P., Brooksbank, K., Hobbs, T., Neumann, C., Lewis, T., Read, Z., Clifford, D., Kmoch, L., Rooney, M., Freudenberger, D., Jonson, J., Peck, A., Giles, R., Bartle, J., McAurthur, G., Wildy, D., Lindsay, A., Preece, N., Cunningham, S., Powe, T., Carter, J., Bennett, R., Mendham, D., Sudmeyer, R., Rose, B., Butler, D., Cohen, L., Fairman, T., Law, R., Finn, B., Brammar, M., Minchin, G., Oosterzee, P.V. & Lothian, A. (2013) Improved estimation of biomass accumulation by environmental planting and mallee plantings using FullCAM. *Report for Department of Climate Change and Energy Efficiency*. pp. 98. Canberra.

Paul, K.I., Roxburgh, S.H., Chave, J., England, J.R., Zerihun, A., Specht, A., Lewis, T., Bennett, L.T., Baker, T.G., Adams, M.A., Huxtable, D., Montagu, K.D., Falster, D.S., Feller, M., Sochacki, S., Ritson, P., Bastin, G., Bartle, J., Wildy, D., Hobbs, T., Larmour, J., Waterworth, R., Stewart, H.T., Jonson, J., Forrester, D.I., Applegate, G., Mendham, D., Bradford, M., O'Grady, A., Green, D., Sudmeyer, R., Rance, S.J., Turner, J., Barton, C., Wenk, E.H., Grove, T., Attiwill, P.M., Pinkard, E., Butler, D., Brooksbank, K., Spencer, B., Snowdon, P., O'Brien, N., Battaglia, M., Cameron, D.M., Hamilton, S., McAuthur, G., Sinclair, J. (2016). Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. *Global Change Biology.* 22(6):2106-24.

Peichl M., & Arain M.A. (2007). Allometry and partitioning of above- and below ground tree biomass in an age-sequence of white pine forests. *Forest Ecology and Management*. 253:68–80.

Pérez-Cruzado, C., Fehrmann, L., Magdon, P., Cañellas, I., Sixto, H., & Kleinn, C. (2015). On the site-level suitability of biomass models. *Environmental Modelling & Software*. 73:14-26.

Roxburgh, S.R., Paul, K.I., Clifford, D., England, J.R., & Raison, R.J. (2015). Guidelines for constructing allomtric models for the prediction of woody biomass: How many individuals to harvest? *Ecosphere*. 6(3):38.

Schenk, H.J., & Jackson, R.B. (2002). Rooting depths, lateral root spreads, and belowground/aboveground allometries of plants in water limited ecosystems. *Journal of Ecology*. 90:480-494.

Soares P., Tome M., Skovsgaard J.P., & Vanclay, J.K. (1995). Evaluating a growth model for forest management using continuous forest inventory data. *Forest Ecology and Management*. 71:251-265.

Snowdon, P. (1991). A ratio estimator for bias correction in logarithmic regressions. *Canadian Journal of Forest Research.* 21:720–724.

Sternberg, M., & Shoshany, M. (2001) Influence of slope aspect on Mediterranean woody formations: a comparison of a semiarid and an arid site in Israel. *Ecological Research*. 16:335-345

Vieilledent, G., Vaudry, R., Andriamanohisoa, S.F., Rakotonarivo, O.S., Randrianasolo, H.Z., Razafindrabe, H.N., Rakotoarivony, C.B., Ebeling, J., & Rasamoelina, M. (2012). Universal approach to estimate biomass and carbon stock in tropical forests using generic allometric models. *Ecological Applications*. 22:572–583.

West, G.B., Brown, J.H., & Enquist, B.J. (1999). A general model for the structure and allometry of plant vascular systems. *Letters to Nature*. 400:664-667.

Williams, R.J., Zerihum, A., Montagu, K.D., Hoffman, M., Hutley, L.B., & Chen, X. (2005). Allometry for estimating aboveground tree biomass in tropical and subtropical eucalypt woodlands: towards general predictive equations. *Australian Journal of Botany*. 53:607–619.

Xiang, W., Liu, S., Deng, X., Shen, A., Lei, X., Tian, D., Zhao, M., & Peng, C. (2011). General allometric equations and biomass allocation of Pinus massoniana trees on a regional scale in southern China. *Ecological Research*. 26:697-711.

Ximenes, F., Gardner, W.D., & Kathuria, A. (2008). Proportion of above-ground biomass in commercial logs and residues following the harvest of five commercial forest species in Australia. *Forest Ecology and Management*. 256:335-346.

Zapata-Cuartas, M., Sierra, C.A., & Alleman, L. (2012). Probability distribution of allometric coefficients and Bayesian estimation of aboveground tree biomass. *Forest Ecology and Management*. 277:173–179.

Zianis, D., & Mencuccini, M. (2004). On simplifying allometric analyses of forest biomass. *Forest Ecology and Management*. 187:311–332.

Appendix G   Brief review of the potential for estimation of biomass by remote sensing

There is active research on methods to estimate biomass in tropical forests using remote sensing techniques, including analysis of spectral indices, and use of SAR and LIDAR. In general these methods require calibration using ground-based data. Saturation may be a problem, especially in tropical countries because the correlation between biomass and the remote sensing data may not be effective at high biomass densities.

A key issue when using tree height (estimated using LIDAR or SAR) to estimate biomass, is that the relationship between height and biomass is likely to differ markedly with forest type, tree age, speciation, and following forest disturbance (e.g. between primary and secondary forest). Such differences need to be understood and taken into account in order to improve estimates of forest biomass and change.

This review suggests that existing large-scale biomass maps derived from remote sensing data need extensive in-country testing to confirm that they are reliable for application in specific forest types and at the spatial scale of interest. Biomass estimation error using remote sensing is high at the plot scale (< 1 ha) and up to 1 sq km (100 ha) (Saatchi et al., 2011) and therefore robust field estimates of biomass based on adequate plot size, sufficient spatial sampling, and use of appropriate allometrics are needed (e.g. Chave, et al., 2004; Avitabile et al., 2011). This means that currently the method is unlikely to be cost efficient.

A brief review of recent work to produce biomass estimates for tropical forests follows.

Use of LIDAR for biomass estimation

Biomass estimates are usually obtained by combining LIDAR data with field observations and sometimes optical data (e.g. MODIS surface reflectance) for obtaining wall-to-wall maps of biomass from point-based estimates as in Baccini et al. (2011).

Baccini et al., (2008) produced a spatial biomass map for Africa by combining remote sensing and field estimates of biomass derived from a range of sources. Mitchard et al., (2011) criticised this map, claiming that the ground data used for calibrating the remote sensing were inadequate, and resulted in significant underestimation of biomass, especially for areas with high biomass densities. Avitabile et.al. (2011) reported poor correspondence between 7 biomass maps (derived either by extrapolation of field estimates of biomass, or derived using remote sensing) for Uganda, both in terms of average biomass densities and spatial patterns. They concluded that the next critical step to increasing reliability of biomass maps was the collection of more reliable field biomass data for key forest types.

Saatchi et.al. (2011) used remote sensing to derive a biomass map for tropical forests at 1 km resolution, and to estimate the errors of biomass estimates made at different spatial scales. They established a relationship between forest stand height and biomass at 493 locations across the tropics. This relationship was able to predict ground estimates of biomass for many other locations with an uncertainty of about 24% on average. Estimates of forest height derived from space-borne LIDAR were then used to estimate biomass at many more locations. The biomass estimates derived from ground measurements and those estimated using LIDAR were then extrapolated across the entire tropical forest using a data-fusion model and satellite imagery from a range of sources. No validation of these new biomass estimates appears to have been undertaken. The authors assumed that their initial field estimates of biomass were error free, but acknowledged that there may have been significant and systematic non-random errors in the estimates used. Analysis by Chave et al. (2004) of the sources of error involved in biomass estimation

at both plot and landscape scale in tropical forests, suggests that such errors were very likely. Chave et al., 2004 provide advice on how to minimize biomass estimation errors, and identified the critical importance of appropriate selection of allometric models which they concluded were a high contributor to uncertainty.

Baccini et al., (2012) used a combination of field data and remote sensing to generate a biomass map for tropical forests at 500m resolution. They used continental allometric models (of moist, dry, and wet forests) to convert field data measurements to forest biomass at a range of locations across several countries, and then correlated biomass with vegetation structure metrics derived from space-borne LIDAR.

Tyukavina et al., (2015) generated a pantropical vegetation stratification based on remotely sensed data and used the space-borne LIDAR biomass estimates from Baccini et al., 2012 to assign a biomass density value to each stratum, in essence using the LIDAR estimates as a surrogate for forest inventory.

Baccini and Asner 2013 reports on the improvements resulting from the substitution of space borne GLAS LIDAR with high resolution airborne LIDAR to calibrate remotely sensed data. They first show the agreement between Baccini et al., 2012 biomass map estimates and independent high resolution LIDAR measurements in the Peruvian and Colombian Amazon and report that pantropical datasets explain about 70% of the variance in biomass, second they show that by fine calibration with airborne LIDAR samples the root mean squared error decreases of about 38-44% and suggest great potential of the integration of airborne LIDAR sampling with space remote sensing to generate wall-to-wall biomass estimates.

Sources of LIDAR

LIDAR systems emit laser pulses and by measuring the timing and intensity of the returns, three-dimensional information on vegetation structure is inferred which in turn allows for prediction of forest structure attributes related to aboveground biomass. The most feasible approach for obtaining biomass estimates from remote sensing data is to make use of LIDAR-based measurements of vegetation structure. There are two main sources of LIDAR data: (1) small footprint, airborne LIDAR data and (2) full waveform, space-borne LIDAR data. At the time of writing there is no operational LIDAR satellite; data availability is limited to what is available from the GLAS instrument on the now defunct ICESat satellite between 2003 and 2009.

Airborne LIDAR data

Airborne LIDAR data, if available for a sample of the study area, can be used to estimate biomass. The LIDAR data provides three-dimensional information on the vegetation structure that can be regressed against plot-level aboveground measurements of biomass to provide biomass estimates for each LIDAR observation. While allometric models exist for a range of conditions which allows for biomass estimation without *in situ* collection of biomass, biomass measurements within the area covered by the LIDAR flight tracks will ensure that regional and local variation in the LIDAR-biomass relationship is included (Asner, 2009). Examples of how to use airborne LIDAR data together with field plots to estimate biomass are provided by: Asner et al., (2010) (IPCC-compliant estimates of carbon stocks and emissions in the Peruvian Amazon); Nelson et al., (2004) (biomass estimation in Delaware, United States); Næsset et al., (2013) (biomass change estimates in boreal forests, Norway); and Lefsky et al., (1999) (biomass estimation in deciduous forests in Maryland, United States).

Satellite LIDAR data

LIDAR observations from space are currently limited to data from the GLAS sensor on board the ICESat. The sensor collected LIDAR data from 2003 to 2009 which is available for free download at NASA Reverb. ICESat-2, which will carry LIDAR instruments, is planned for launch in early 2016. No other missions are planned at the time of writing. Therefore there is a data gap in space borne LIDAR observations between 2009 and 2015.

Research indicates that, while it is possible to estimate tree height from ICESat/GLAS data which in turn can be regressed to obtain biomass estimates (Sun et al., 2007), estimating tree height from GLAS data is less straightforward compared to using airborne, small footprint LIDAR data. On sloped areas, topographic information is required to estimate tree height because of the elliptical shape of the GLAS footprint (Lefksy et al., 2005). Sources that provide descriptions of using GLAS data for estimating tree height and biomass include: Baccini et al., 2012; Saatchi et al., 2011; Nelson et al., 2008; Boudreau et al., 2008; Lefksy et al., 2005.

Existing large-scale biomass products include:

▶ *The National Level Carbon Stock Dataset (Tropics)* Woods Hole Research Center (WHRC) provides maps of above-ground live woody biomass for the tropics. Using a combination of field measurements and space-borne LIDAR observations at 70 m spatial resolution from the Geoscience Laser Altimeter System (GLAS) instrument on board the Ice, Cloud and land Elevation Satellite (ICESat), and optical MODIS imagery at 500 m spatial resolution, the WHRC National Level Carbon Stock Dataset provides above-ground live woody biomass at 500 m resolution for the tropics 2007-2008 (Baccini et al., 2012). The data are available online.

▶ *The National Biomass and Carbon Dataset (NBCD2000)* WHRC provides a 30 m biomass product for the conterminous United States. This map does not cover tropical areas, but it provides a model for how NFI plot data can be combined with remote sensing data to make maps of biomass. NBCD2000 is based on a combination of data from the USDA Forest Service Forest Inventory and Analysis (FIA), the 2000 Shuttle Radar Topography Mission (SRTM) and Landsat-7/ ETM+. It provides basal area-weighted canopy height, aboveground live dry biomass, and standing carbon stock for the year 2000 (Kellndorfer, et al., 2010).

▶ *The JPL Carbon Maps.* The Jet Propulsion Laboratory of NASA and the California Institute of Technology provide a biomass product similar to that of the WHRC National Level Carbon Stock Dataset. The maps provide forest above-ground carbon and biomass for sub-Saharan Africa, the Americas south of latitude 30° N, and South-East Asia and Australia between the latitudes of 40° N and 30° S at 1 km resolution. Point-based estimates of biomass generated from a combination of field data and space-borne LIDAR data from ICESat/GLAS were extrapolated using optical data from MODIS and SAR data from SRTM and QuickSCAT (Saatchi et al., 2011).

Use of synthetic aperture radar (SAR) for biomass estimation

Although synthetic aperture radar (SAR) has demonstrated potential in the estimation of aboveground biomass, there are limitations arising from:

▶ for some bands, rapid saturation of the signal at low aboveground biomass stock

▶ terrain

▶ rainfall and soil moisture effects

▶ localised algorithm development focussing on a single biome or mono-species stands

▶ lack of consistency in estimates as a function of sensor parameters.

Calibration of the retrieval algorithm depends on reliable ground data, which need to be collected under a representative range of environmental conditions. As such, there is limited transferability of algorithms within and between different forest structural types and, so far, no reliable means of estimating aboveground biomass (Lucas et al., 2010).

Recent work in Australia as focused on collating, at a national level, forest inventory data that has been collected by various agencies and individuals since the 1990s. Measurements of the size (e.g., diameter) of individual trees have been used as input to standardized allometric models to generate tree and subsequently stand-level estimates of above and also below ground biomass. Estimates of uncertainty have also been provided, with these considering the errors associated with the measurement of individual trees, the application of different allometric models and the scaling from the tree to the plot level. The intention of the biomass library is to facilitate continual upload of forest inventory data in return for tree and stand level biomass estimates which, in turn, will be released publicly. As well as providing data to support, for example, carbon cycle science, the data are also intended to support the development and validation of algorithms for the retrieval of biomass at national to global levels from past, current and future sensors including ESA's BIOMASS Mission, JAXA's ALOS-2 PALSAR-2 and NASA's NiSAR and GEDI.

SAR based estimation of aboveground biomass has been more successful in temperate forests compared to tropical forests, due largely to fewer species and lower biomass (Castro et al., 2003). Increased sensitivity has been achieved using ratios or correlations between multi-frequency, multi-polarisation backscatter and biomass components (Castro et al., 2003). Alternative approaches, including SAR interferometry, polarimetric interferometry, tomography and integration with LIDAR and other data are the focus of current investigations.

SAR has a demonstrated capacity to quantify biomass up to a certain level, depending on the frequency used. Once saturation of the signal is reached, the data are no longer useful for biomass estimation (Bottcher et al., 2007 and 2009; Gibbs et al., 2007). Cross-polarised backscatter demonstrates greater sensitivity to forest biomass than co-polarised backscatter, however, the use of multiple polarisations is recommended for use in retrieval algorithms (Castro et al., 2003). L-band SAR is useful for discriminating regrowth stage and estimating biomass in low biomass (40-150 t/ha) forests. Dual polarisation and dual-season coverage is required. C-band SAR is only useful in very low biomass forests (30-50 t/ha). The shorter wavelength does not penetrate further than the leafy canopy (Castro et al., 2003). Texture analysis of multi-temporal, high resolution C-band data may provide some useful input (Castro et al., 2003).

ESA has recently approved the BIOMASS mission, a P-band interferometer which will provide global scale estimation of aboveground biomass in the 2020 timeframe. P-band SAR can facilitate biomass estimation in high biomass (100-300 t/ha) forest.

Sub-national demonstrations

Biomass estimating using SAR requires sophisticated processing and extensive ground calibration, and while the research is progressing, there are few demonstrations at sub-national scale. Successful

demonstrations have largely relied on GFOI non-core data streams, including airborne (GeoSAR) and satellite SAR (ALOS PALSAR, ENVISAT ASAR).

▸ Eastern Australia: Relationships established between ALOS PALSAR L-HH and HV backscatter and field measured AGB led to the production of an interim AGB map (Lucas et. al., 2010). Validation underway. Improvements likely through the integration of Landsat and ICESat data products

▸ Mexico: Wall-to-wall AGB map produced using ALOS PALSAR data acquired in 2008 at 15 m spatial resolution (GEO, 2011)

▸ North-eastern USA: Inversion of semi-empirical model calibrated for ALOS PALSAR FBD images to estimate biomass (Cartus et al., 2012). Retrieval accuracy for HV intensity data was consistently better than for HH. Weighted combinations of single-date biomass estimates in a multi-temporal stack significantly improved performance. RMSE of 12.9 t/ha (R^2 = 0.86) compared to forest inventory

▸ Boreal forest: Model based estimation of growing stock volume (GSV) up to 300 m3/ha using hyper-temporal ENVISAT ASAR ScanSAR images (Santoro, et. al., 2011). RMSE of 34.2 – 48.1 % at 1 km pixel size. GSV was improved by averaging over neighbouring pixels. Transferability of method to tropical forest requires investigation

▸ Woody vegetation in Queensland, Australia: the study aimed to establish whether the relationship between PALSAR HH and HV backscattering coefficients and AGB was consistent within and between structural formations (forests, woodlands and open woodlands, including scrub). The study examines saturation and concludes that PALSAR data acquired when surface moisture and rainfall are minimal allow better estimation of the AGB of woody vegetation and that retrieval algorithms ideally need to consider differences in surface moisture conditions and vegetation structure (Lucas et al., 2010).

References

Asner, G.P. (2009). Tropical forest carbon assessment: integration satellite and airborne mapping approaches. Environmental Research Letters, 4(3), 034009.

Asner, G.P., Powell, G.V.N., Mascaro, J., Knapp, D.E., Clark, J.K., Jacobson, J., Kennedy-Bowdoin, T., Balaji, A., Paez-Acosta, G., Victoria, E., Secada, L., Valqui, M. & Hughes, R.F. (2010). High-resolution forest carbon stocks and emissions in the Amazon. Proceedings of the National Academy of Sciences, 107: 16738-16742.

Avitabile, V., Herold, M., Henry, M., & Schmullius, C. (2011). Mapping biomass with remote sensing: a comparison of methods for the case study of Uganda. *Carbon Balance and Management*. 6:7.

Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P.S.A., Dubayah, R., Friedl, M.A., Samanta, S., Houghton, R.A. (2012). Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*. 2:182-185.

Baccini A. & Asner, G.P. (2013). Improving pantropical forest carbon maps with airborne LIDAR sampling. *Carbon Management*. 4(6):591–600.

Cartus, O., Santoro, M., & Kellndorfer, J. (2012). Mapping forest aboveground biomass in the Northeastern United States with ALOS PALSAR dual-polarisation L-band. *Remote Sensing of Environment*. 124:466-478.

Castro, K.L., Sanchez-Azofeifa, G.A., & Rivard, B. (2003). Monitoring secondary tropical forests using space-borne data: implications for Central America. *International Journal of Remote Sensing*. 24:1853-1894.

Chave, J., Condit, R., Aguilar, S., Herandez, A., Lao, S. & Perez, R. (2004). Error propagation and scaling of tropical forest biomass estimates. *Philosophical Transactions B. Royal Society London*. 359:409-420.

GEO, (2011). Observations, Group on Earth.GEO-FCT Product Development Team Technical Status Report v2.0. s.l. : GEO, 2011.

Gibbs, H.K., Brown, S., Niles, J.O., & Foley, J.A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters*. 2:045023.

Kellndorfer, J.M., Walker,W.S, LaPoint, E., Kirsch, K., Bishop, J., & Fiske, G. (2010). Statistical fusion of lidar, InSAR, and optical remote sensing data for forest stand height characterization: A regional-scale method based on LVIS, SRTM, Landsat ETM+, and ancillary data sets. *Journal of Geophysical Research*. 115 G00E08.

Lucas, R., Armston, J., Fairfax, R., Fensham, R., Accad, A., Carreiras, J., Kelley, J., Bunting, P., Clewley, D., Bray, S., Metcalfe, D., Dwyer, J., Bowen, M., Eyre, T., Laidlaw, M., & Shimada, M. (2010). An Evaluation of the ALOS PALSAR L-Band Backscatter—Above Ground Biomass Relationship Queensland, Australia: Impacts of Surface Moisture Condition and Vegetation Structure. *IEEE Journal of Selected Topics in Applied Earth Observation and Remote Sensing*. 3:576-593;

Mitchard, E. T. A., Saatchi, S. S., Lewis, S. L., Feldpausch, F. F., Woodhouse, I. H. and P. Meir (2011). Comment on a First map of tropical forest biomass derived from satellite imagery. *Environmental Research Letters*. 6:049001

Næsset, E., Bollandsås, O.M., Gobakken, T., Gregoire, T.G. & Ståhl. G. (2013). Model-assisted estimation of change in forest biomass over an 11 year period in a sample survey supported by airborne LIDAR: A case study with post-stratification to provide activity data. *Remote Sensing of Environment*. 128:299-314.

Saatchi, S.S., Houghton, R.A., dos Santos Alvalá, R.C., Soares, J.V., Yu, Y. (2007). Distribution of aboveground live biomass in the Amazon basin. *Global Change Biology*. 13:816-837.

Santoro, M, Beer, C., Cartus, O., Schmullius, C., Shvidenko, A., McCallum, I., Wegmüller, U., Wiesmann, A. (2011). Retrieval of growing stock volume in boreal forest using hyper-temporal series of Envisat ASAR ScanSAR backscatter measurements. *Remote Sensing of Environment*. 115:490-507.

Tyukavina A., Baccini, A., Hansen, M.C., Potapov, P.V., Stehman, S.V., Houghton, R.A., Krylov, A.M., Turubanova, S., & Goetz, S.J. (2015). Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012. *Environmental Research Letters*. 10(7): 74002.