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 3.0

GFOI

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Advisory Group

Chair: María José Sanz (Basque Centre for Climate Change; Spain)

Members:

Sandro Federici (IPCC Technical Support Unit; Japan)	Ake Rosenqvist (Committee on Earth Observation Satellites)
Mwangi Kinyanjui (Karatina University; Kenya)	Rene Siwe (US Forestry Service; Cameroon)
Haruni Krisnawati (Forestry Research and Development Agency; Indonesia)	Rob Waterworth (Mullion Group; Australia)
Dalton de Morisson Valeriano (INPE; Brazil)	Yasumasa Hirata (Forestry and Forest Products Research Institute; Japan)
Dirk Nemitz (UNFCCC Secretariat; Germany)	Mikaela Weisse (World Resources Institute; United States)
Elizabeth Philip (Ministry of Natural Resources and Environment; Malaysia)	Curtis Woodcock (Boston University; United States)

Lead Author Team

Andres Espejo (World Bank, United States)	Pontus Olofsson (Boston University; United States)
Sandro Federici (IPCC Technical Support Unit; Japan)	María José Sanz Sánchez (Basque Centre for Climate Change; Spain)
Carly Green (Environmental Accounting Services; Australia)	Rob Waterworth (Mullion Group, Australia)

Author Team

Naikoa Amuchastegui (World Wildlife Fund, United States)	Christoph Kleinn (Georg-August-University Göttingen; Sweden)
Rémi d'Annunzio (Food and Agricultural Organization of the United Nations; Rome)	Werner Kurz (Canadian Forest Service)
Heiko Balzter (Leicester University; United Kingdom)	Erik Lindquist (Food and Agricultural Organization of the United Nations; Italy)
Pradeepa Bholanath (Guyana Forestry Commission; Guyana)	Ronald McRoberts (United States Forest Service)
Cris Brack (Australian National University, Australia)	Anthea Mitchell (University of New South Wales, Australia)
Charles Brewer (United States Forest Service)	Erik Næsset (Norwegian University of Life Sciences)
Luca Birigazzi (UNFCCC Secretariat; Germany)	Evan Notman (Global Forest Observations Initiative; Italy)
Edersson Cabrera (Instituto de Hidrología, Metereología y Estudios Ambientales; Colombia)	Shaun Quegan (University of Sheffield; United Kingdom)
Sarah Carter (Wageningen University, Netherlands)	Ake Rosenqvist (solo Earth Observation; Japan)
Narendra Chand (Independent Consultant; Fiji)	Stephen Roxburgh (Commonwealth Scientific and Industrial Research Organization, Australia)
Danny Donoghue (Durham University; United Kingdom)	Christophe Sannier (Systèmes d'Information à Référence Spatiale; France)
Simon Eggleston (GCOS; Switzerland)	Charles Scott (United States Forest Service)
Nikki Fitzgerald (Department of Industry, Australia)	Göran Ståhl (Swedish University of Agricultural Sciences)
Giles Foody (University of Nottingham, United Kingdom)	Stephen Stehman (State University New York; United States)

Gustavo Galindo (Instituto de Hidrología, Metereología y Estudios Ambientales; Colombia)	Viliame Tupua (Ministry of Forestry; Fiji)
Grant Domke (United States Forest Service)	Pete Watt (Indufor Asia-Pacific; New Zealand)
Sara Goeking (United States Forest Service)	Sylvia Wilson (United States Geological Survey)
Giacomo Grassi (Joint Research Centre, European Commission)	Curtis Woodcock (Boston University)
Alex Held (Commonwealth Scientific and Industrial Research Organisation, Australia)	Mike Wulder (Canadian Forest Service)
Martin Herold (Wageningen University; Netherlands)	

Reviewers

Gilberto Câmara (National Institute for Space Research; Brazil)	Inge Jonckheere (Food and Agricultural Organization of the United Nations; Italy)
Jerome Chave (Paul Sabatier University; France)	Andrew Lister (United States Forest Service)
Nagmeldin Elhassan (Higher Council for the Environment and Natural Resources, Sudan)	Aristides Muhate (Fundo Nacional de Desenvolvimento Sustentável; Moçambique)
Africa Flores (NASA; United States)	Dirk Nemitz (UNFCCC Secretariat; Germany)
Giles Foody (Nottingham University; United Kingdom)	Carla Ramirez (Food and Agricultural Organization of the United Nations; Italy)
Sabin Guendehou (UNFCCC Secretariat; Germany)	Frank-Martin Seifert (European Space Agency; Italy)
Tom Harvey (Global Forest Observations Initiative; Rome)	Mikaela Weisse (World Resources Institute; United States)
Mohamed Elgamri Ibrahim (Sudan University of Science and Technology)	

Acronyms

Acronym	Term
2006GL	2006 IPCC Guidelines for National Greenhouse Gas Inventories
96GL	1996 Revised IPCC Guidelines for National Greenhouse Gas Inventories
AFOLU	Agriculture, Forestry and Other Land Use
AGB	Above-Ground Biomass
ALOS	Advanced Land Observing Satellite (Japanese series)
ALS	airborne laser scanning
ALU	Agriculture and Land USE National GHG Inventory Software
AR	Afforestation/Reforestation
ARD	Afforestation/Reforestation/Deforestation
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
BNCR	Bureau National de Coordination REDD+ Madagascar
BR	Biennial Report
BTR	Biennial Transparency Report
BUR	Biennial Update Reports
CBERS	China-Brazil Earth Resources Satellite series
CBM-CFS3	Carbon Budget Model of the Canadian Forest Sector
CCDC	Continuous Change Detection and Classification
CDM	Clean Developmentt Mechanism
CEOS	Committee on Earth Observation Satellites
CF	Carbon Fraction
CI	Confidence Interval
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
COP	Conference of Parties to the UNFCCC
CPU	Central Processing Unit
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSO	Civil Society Organisation
CV	Co-efficient of Variation
DRC	Democratic Rebublic of Congo
EF	Emission Factor
EO	Earth Observation
ESA	European Space Agency
EW	Early Warning
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

Acronym	Term
GCF	Green Climate Fund
GEDI	Global Ecosystem Dynamics Investigation
GEO	Group on Earth Observations
GFOI	Global Forest Observations Initiative
GHG	Greenhouse Gas
GHGI	Greenhouse Gas Inventory
GIS	Geographical Information System
GLAD	Global Land Analysis & Discovery
GLAS	Geoscience Laser Altimeter System
GOFC-GOLD	Global Observation of Forest Cover-Global Observation of Land Dynamics
GPG2000	2000 Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories
GPG2003	2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry
GPS	Global Positioning System
GREG	Model-Assisted Generalised Regression Estimator
HLS	Hamonized Landsat Sentinel-2
ICA	International Consultation and Analysis
IceSAT	Cloud and land Elevation Satellite
IDE	Interactive development environment
INCAS	Indonesia’s Carbon Accounting System
INDC	Intended National Determined Contributions
INEGI	Mexican National Statistical and Mapping Agency
IPCC	Intergovernmental Panel on Climate Change
IRS	Infrared system
ISO	International Organization for Standardization
ISRO	Indian Space Research Organisation
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
KCA	Key Category Analysis
KP	Kyoto Protocol
L1G	Landsat Level 1 Georectified
L1T	Landsat Level 1 Orthorectified
LAMP	LiDAR-Assisted Multi-Source Program
LANDSAT	Land Satellite (US Satellite series)
LDC	Least developed countries
LiDAR	Light Detection and Ranging
LULUCF	Land use, Land-Use Change and Forestry
MGD	Methods and Guidance Document
MMU	Minimum mapping unit
MODIS	Moderate Resolution Imaging Spectroradiometer (US satellite series)
MOLI	Multi-footprint Observation LiDAR and Imager

Acronym	**Term**
MOU	Memorandum of Understanding
MRV	Measurement, Reporting, and Verification
NAMA	Nationally Appropriate Mitigation Action
NASA	National Aeronautics and Space Administration
NC	National Communication
NDC	Nationally Determined Contribution
NFI	National Forest Inventory
NFMS	National Forest Monitoring System
NISAR	NASA-ISRO Synthetic Aperture Radar
NMVOC	Non-methane volatile organic compounds
OECD	Organisation for Economic Co-operation and Development
OLCI	Ocean and Land Colour Instrument
PA	Paris Agreement
PNCBMCC	National Program for the Conservation of Forests for Climate Change, Peru
PSOE	Present, Suitable, Operational, Effective
PSTR	Post-stratification
QA/QC	Quality Assurance and Quality Control
RACI	Responsible, Authority, Consulted, Informed
RADAR	Radio Detection and Ranging
RADARSAT	Canadian SAR satellite series
RE	Relative Efficiency
REDD+	Reducing Emissions from Deforestation and forest Degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks (REDD+).
SAOCOM	Argentine Microwaves Observation Satellite series
SAR	Synthetic Aperture Radar
SE	Standard Error
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SIACON	Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food of Mexico
SIDS	Small Island Developing States
SLEEK	Systems for Land-based Emissions in Kenya
SOP	Standard operating procedures
SPOT	Satellite Pour l'Observation de la Terre (French satellite series)
SRS	Simple Random Sampling
SRTM	Shuttle Radar Topography Mission
STR	Stratified Sampling
SWIR	Shortwave Infrared
SYS	Systematic Sampling
TA	Technical Assessment
TACCC	Transparency, Accuracy, Consistency, Comparability, Completeness
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement (Germany)

Acronym	Term
TER	Technical Expert Review
TerraSAR-X	SAR Earth Observation Satellite (Germany)
TERT	Technical Expert Review Team
TR	Technical Review
TTE	Technical Team of Experts
UN	United Nations
UN-REDD	United Nations Collaborative Initiative on Reducing Emissions from Deforestation and forest Degradation (REDD)
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
VNIR	Visual and Near Infrared

Explanation of Key Terms

For a complete Glossary of IPCC terms, refer to **2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories**

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 Volume 4, Chapter 3; 2006 IPCC Guidelines**
Anthropogenic emissions and removals	Anthropogenic emissions and removals means that greenhouse gas emissions and removals included in national inventories are a result of human activities.	In the Agriculture, Forestry and Other Land Use (AFOLU) Sector, emissions and removals on managed land are taken as a proxy for anthropogenic emissions and removals (Managed Land Proxy), and inter-annual variations in natural background emissions and removals, though these can be significant, are assumed to average out over time.	**Volume 1, Chapter 1; 2019 Refinement**
Emission or removal factors	Greenhouse gas (GHG) emissions or removals per unit of activity data.		**Chapter 3; GPG2003 Volume 4, Chapter 2; 2006 IPCC Guidelines**
Forest Monitoring	Functions of a National Forest Monitoring System to assist a country in meeting 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 Greenhouse Gas Inventories (GHGIs)	COP decisions **12/CP.17**, **13/CP.19** and **14/CP.19** see also **UNFCCC factsheet on FREL/FRL**
Greenhouse Gas Inventory	Anthropogenic greenhouse gas estimates with national territorial coverage produced using Intergovernmental Panel on Climate Change (IPCC) methods in accordance with decisions taken at the United Nations Conference Framework Convention on Climate Change (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. **Decision 12/CP.17** requires Forest Reference Emission Levels (FRELs) and Forest Reference Levels (FRLs) to maintain consistency with anthropogenic forest related emissions and removals in GHGIs, and **decision 14/CP.19** requires consistency between emissions and removals reported for REDD+ activities and FRELs or FRLs.	| COP **decision 4/CP.15** requests 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/CP.17** 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 can presumably be referred to on a voluntary basis.
Ground-based data or ground-based observations	Data gathered by measurements made in the field.	Field measurements could also be regarded as remotely sensed if the point of measurement is distant from what is being measured (i.e. LiDAR or gaseous concentrations).	

Concept	**Meaning**	**Notes**	**Example reference (where applicable)**
Institutional Arrangements	The United Nations Development Programme (UNDP) describes institutional arrangements as being policies, systems and processes that organisations (including governments) use to legislate, plan and manage their activities efficiently and coordinate with others in order to fulfill respective mandates.		For example, countries can move from 'brain drain' to 'brain gain' by creating incentives to encourage skilled workers to remain, to return after university, or to engage in specific projects on a short-term basis. Such an effort could involve universities, public administration and the private sector.
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.). 2010. Springer.
National Forest Monitoring System (NFMS)	The arrangements in a country to monitor forests, including foundational, strategic and operational system elements. In the REDD+ context, the NFMS is 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 remotely-sensed and ground- based data, provide estimates that are transparent, consistent, as far as possible accurate, and which reduce uncertainties, taking into account national capabilities and capacities; and that their results are available and suitable for review as agreed by the COP. An 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+ countries	A developing country that has voluntarily opted to report emissions and removals from REDD+ activities in the context of results based payments.	REDD+ stands for countries' efforts to reduce emissions from deforestation and forest degradation, and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks.	

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 remotely sensed data, 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 data to correct for classification bias. The latter approach may be more resource-efficient. Reference data are often ground-based data, although high-quality remotely-sensed data can also be used.	
Remotely Sensed Observations	Acquiring and using data from satellites, aircraft, close-range remote sensing 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, Jensen, J. 2004.
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 classification algorithms.	Training data can be obtained from ground-based sources or from other remotely sensed data, such as high resolution data.	
Uncertainty	Lack of knowledge of the true value of a variable that can be described as a probability density function characterising the range and likelihood of possible values.	Uncertainty depends on the analyst's state of knowledge, which in turn depends on the quality and quantity of applicable data as well as knowledge of underlying processes and inference methods.	For more detailed explanation of other terms related to uncertainty, see **IPCC, 2006. Volume 1, Chapter 3**.

Concept	**Meaning**	**Notes**	**Example reference (where applicable)**
Uncertainty assessment	An uncertainty assessment is used by inventory compilers to improve inventories over time.	The process of producing an uncertainty assessment can pragmatically be divided into four parts: (1) the rigorous investigation of the likely causes of data uncertainty; (2) the development of quantitative uncertainty estimates and parameter correlations; (3) the mathematical combination of those estimates when used as inputs to a statistical model (e.g. first-order error propagation or Monte Carlo method); and (4) the selection of inventory improvement actions (improvement plan) to take in response to the results of the previous three parts.	
Verification	Verification refers to the collection of activities and procedures conducted during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of the inventory.	It is important to distinguish verification, as defined by the IPCC guidelines, from the term verification used in carbon markets, which is synonymous with an independent audit.	For more detailed explanation of verification, see **IPCC, 2019. Volume 1, Chapter 6**.

Executive Summary

The Methods and Guidance Document (MGD) is produced by the Global Forest Observations Initiative (GFOI) (**Box 1**). The MGD provides user-friendly guidance for linking UNFCCC decisions related to REDD+ Measurement, Reporting, and Verification (MRV) with IPCC guidance, as in general, the IPCC guidelines and guidance do not identify REDD+ activities.

Specifically, advice is presented on the production of reliable, replicable estimates on change in forest cover and associated emissions for reporting on international agreements, based on the accumulated experience of the joint use of remotely sensed and ground-based data.

This is Edition 3 of the MGD. It updates Edition 2 (published in 2016), taking account of:

- relevant recent developments within the UNFCCC negotiations relating to forest lands;
- methodological advances published in the **2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (the 2019 Refinement);**
- increases in data availability and new research; and
- utility of the methods described in meeting broader national and international forest related monitoring objectives.

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

- **User Group 1 -** responsible for the design and implementation of decisions to meet MRV requirements of national forest monitoring systems.
- **User Group 2 -** 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.

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 in the sharing of data and experiences. It aims to complement guidance from the IPCC, the approaches taken by initiatives supported by the GFOI partners(1), including the United Nations Collaborative Initiative on Reducing Emissions from Deforestation and forest Degradation (**UN-REDD programme**), the **US SilvaCarbon program**, the **World Bank Forest Carbon Partnership Facility** and the **REDD Early Movers programme** as well as a number of other relevant programmes.

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; it guides users through the various steps in setting up REDD+ reference levels and estimating emissions and removals associated with REDD+ activities. The MGD also highlights, where relevant, how a well-designed and functional system for the measuring, reporting and verification of emissions for

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(1) Currently comprising representatives from the Governments of Australia, Germany, Norway, the United Kingdom of Great Britain and Northern Ireland and the United States of America, as well as the international Committee on Earth Observation Satellites (CEOS), the European Space Agency (ESA), the Food and Agriculture Organization of the United Nations (FAO), and the World Bank.

REDD+ can 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 other country reporting goals, including, for example, the **Global Forest Resource Assessment of the Food and Agriculture Organization of the United Nations**, the **Convention on Biological Diversity** and the **Convention to Combat Desertification**.

Box 1: The Global Forest Observations Initiative

The Global Forest Observations Initiative (GFOI) was established under Group on Earth Observations (GEO) in 2011 and is a global partnership for coordinating the delivery of international support in forest monitoring to address developing country needs. Through the collaborative action of its partners, GFOI aims to assist countries to produce reliable, consistent reports on change in forest cover and forest use, and associated anthropogenic greenhouse gas emissions and removals. Partners coordinate their activities under GFOI's four central components:

- **Capacity Building Component -** seeks to develop a common understanding of country needs, and facilitate the choices of countries in designing, developing and operating their own NFMS. GFOI capacity building partners directly support countries in developing these systems and associated capacities. This includes facilitating coordinated hands-on assistance, collaborative training, workshops, short courses, expert exchanges and other methods of knowledge and technology transfer.
- **Data Component -** supports the acquisition, availability, accessibility and capacity for countries to use data sets, tools and services for forest monitoring and GHG accounting according to country-specific requirements around the globe. The Data Component focuses on the role of space and non-space (in situ) data sets, along with the tools and services for discovery, access and application of data, with the intent of helping countries to improve their forest monitoring systems and associated capabilities. Specifically through the work of GFOI lead partner, the Committee of Earth Observation Satellites (CEOS), GFOI works with international space agencies to coordinate access to annual wall-to-wall coverage of all the world's forested regions with remotely sensed data.
- **Methods and Guidance Component -** 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 the IPCC.(2)
- **Research and Development Coordination Component -** fosters a community of experts to address knowledge gaps, progress new technologies and pursue continuous improvements. The Component identifies emerging science and technologies, which can

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(2) This is required by decisions of the UNFCCC for voluntary implementation of REDD+ activities. The REDD+ activities as listed in the Cancun Agreements (**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.

improve monitoring efforts and address unmet country needs. One of the key outputs of this component is to provide a regular forum for the progression of research topics towards operational solutions and guidance. Once solutions have been identified and proven ready for use, these can then be proposed for inclusion in new MGD modules and subsequently used in capacity building activities with countries.

Purpose and Scope

The GFOI MGD provides practical advice related to the development of a National Forest Monitoring System to help meet national and international reporting requirements by:

- providing user-friendly guidance for linking UNFCCC decisions with IPCC guidance;
- focusing on how remotely sensed and ground-based data can be effectively combined to improve estimation of predominately forest related GHG emissions and removals, including those related to GHG inventories, REDD+ activities, and Nationally Determined Contributions (NDCs);
- addressing a gap that would otherwise exist in practical guidance on developing and implementing REDD+ MRV, while maintaining broader relevance to multipurpose monitoring of changes between forest land and non-forest land, particularly the methodologies that are outlined relating to land representation;
- 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;
- highlighting where relevant the broader applicability of the methods described in the development of a multipurpose monitoring system.(3)

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

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. Recognising the needs of these 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 users to navigate and focus on material and tools relevant to them;
- presents case studies or examples where possible to enhance readers' understanding of the advice presented; and
- is provided in both printed and web-based formats through the MGD web application **REDDcompass**, which provides online access to the MGD, as well as to a suite of MGD consistent training materials and tools.

The MGD recognises the importance of MRV requirements and of national circumstances, for determining the mix of remotely sensed and ground-based observations available to countries.

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(3) A multipurpose monitoring system would be capable of meeting broad NFMS objectives, for example a national report to inform and support various policy objectives, as well as international reports to the **Global Forest Resource Assessment of the Food and Agriculture Organization of the United Nations**, the **Convention on Biological Diversity** and the **Convention to Combat Desertification**.

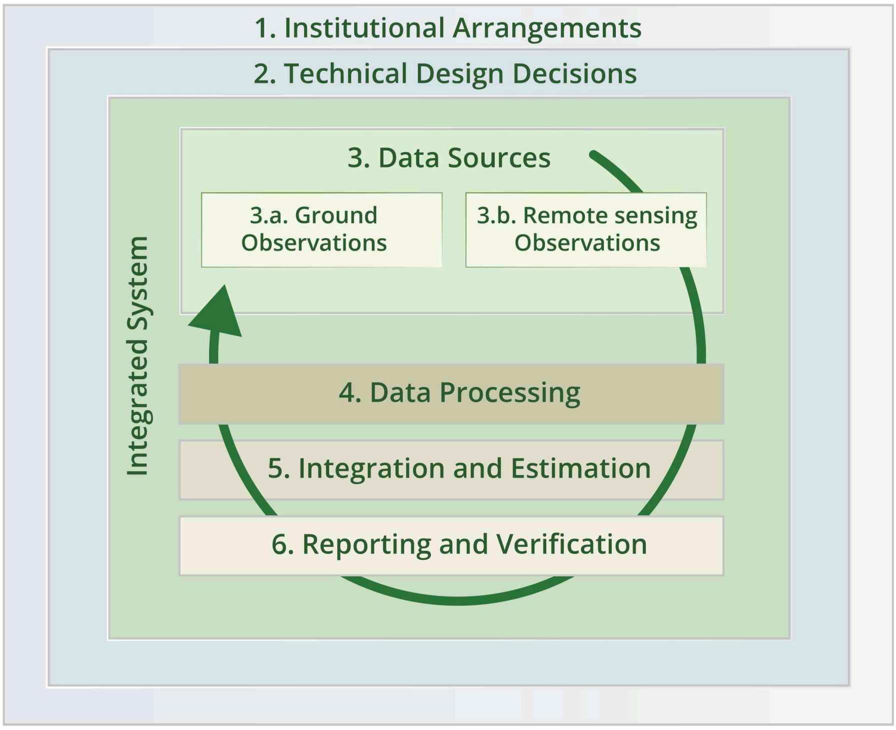
Relevant national circumstances, which may evolve over time, include the:

- level of engagement by government entities; national policy and reporting needs, mitigation planning and tracking of progress;
- history and drivers of forest use and conversion from forest to other land uses;
- nature and availability of historical remotely sensed and ground data;
- availability of technical expertise and institutional capacity to acquire, process and analyse 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; and
- financial resources available to design, build and operate MRV systems.

Structure

The MGD is structured to relate guidance and advice to various generic components of an NFMS (**Figure 1**), while also noting each individual country context. In general terms, an NFMS has technical components (boxes) and processes (arrows), which are fully interdependent, and as such must be fully integrated for the effective operation of the NFMS.

Figure 1: The general context for a National Forest Monitoring System



The MGD recognises that most NFMSs are built on some form of existing basis and typically start with the available data and the filling of identified data gaps. However, it is inevitable that as **systems mature** and new **monitoring and reporting goals** emerge, system improvements, or in some cases overhauls, may be required. Through considered **Technical Design Decisions** combined with an operational **continuous improvement cycle**, a multipurpose NFMS can emerge that meets a range of reporting indicators, including emissions/removals for **REDD+**, a **Greenhouse Gas Inventory (GHGI), Biennial Update Report (BUR) and Biennial Transparency Report (BTR)**, and other reporting, planning and management needs.

1. **Institutional Arrangements** - Building on and strengthening existing institutional arrangements in establishing an NFMS for any new MRV functions will reduce duplication of effort and costs, facilitate use of official data sources, avoid institutional conflicts and help to maximise co-benefits and consistency in reporting. The NFMS process requires clear definitions of roles and responsibilities, as well as necessary arrangements among the institutions to be involved. This is fundamental, not only for successful implementation of the technical processes of the NFMS, but also for its long-term sustainability. The establishment of foundational, strategic and operational structures will enable the NFMS to become an ongoing repeatable function within national government institutions that can support the national reporting objectives and meet

international verification requirements.

2. **Technical Design Decisions** - The NFMS will most likely be reporting under different national and international frameworks to meet country reporting obligations. These frameworks will define aspects such as spatial and temporal scope, periodicity of reporting, precision requirements, implications for performance, how reference levels are to be defined, etc. A clear understanding of design implications and overlaps and differences is fundamental, so as to be able to optimise the NFMS processes to meet national reporting objectives while also maintaining a balance with national resources and capacity. An NFMS should be designed as an ongoing programme within well established and sound **institutional arrangements** and well-considered design decisions, so as to enable it to operate sustainably to meet national reporting commitments and ideally inform broader National policy objectives. It is also important to be mindful of the state of knowledge/science gaps, as these are evolving, and help to improve delivery and understanding.

3. **Data Sources** - Adequate and consistent supply of data for the NFMS implies the establishment of **institutional arrangements** that enable the long term availability of human and logistical resources, technical capacity and the establishment of partnerships and funding. As part of an integrated system data sources need to complement and inform each other so that **design decisions**, such as **stratification**, as well **operational elements**, such as **processes** and **information management** are optimised not for each separate task but for their combined performance. This involves building strong relationships and linkages between remotely sensed and ground-based observations which should be treated as complementary rather than utilitarian (e.g. sampling needs to be designed where both data sources are part of a single integrated system and not two separate ones whose results are to be combined later).

    a. **Ground-based observations** - It is important to consider the relationship between ground data and remotely sensed data with respect to how they will be used and combined in an NFMS, in particular, the compatibility of the geometry of the ground plot and that of the pixel or the minimum mapping unit (MMU) of the remotely sensed data. Other important factors include the spatial and temporal sample designs of the ground data collection, which might not be appropriate for a particular application of remotely sensed data. The periodic nature of ground data collection cycles, particularly from National Forest Inventories (NFI) which are completed typically every 5 to 10 years, can also influence the way in which ground data are integrated in the NFMS, particularly in how it is used to inform not only change classes but also the stable classes.

    b. **Remote sensing observations** - When assessing the utility of remotely sensed observations to support reporting requirements, consideration of forest definition, temporal and spatial resolution, budget for acquisition and means of processing are highly relevant. Long-term sustainability of capacities is key for consistency and for operationalising the NFMS.

4. **Data Processing** - Once data have been acquired, these need be combined to deliver final estimates of GHG emissions and removals, including an estimation of overall uncertainty as per the IPCC good practice guidelines. This must all be done based on appropriate data sources and methods according to the reporting framework and context.

5. **Integration and Estimation** - Monitoring and reporting requirements must drive the analysis and interpretation, allowing for optimisation of data sources and methods for integrating them during estimation. The policy and reporting objectives that the data has to support will define

how the information will be used and therefore integrated.

6. **Reporting and Verification** - Examples of reporting outputs from the NFMS include **Forest Reference Emissions Levels (FREL) and/or Forest Reference Levels (FRL)**, Biennial Updated Reports (BURs) and GHG inventories (under the UNFCCC), performance based payments reports (REDD+ Annex to the BUR, and other schemes), Biennial Transparency Reports under the Paris Agreement or even the Paris Agreement **Global Stocktake**. These will differ according to the guidelines specific to each reporting framework as set by the **goals and scope** of the NFMS. Although some may have overlapping requirements or be based on the same data, they may have different interpretation as per the pertinent framework (e.g. historic average vs. historic-adjusted vs. projected). Reporting and verification are critical outputs of the NFMS, as they support the transparency and quality of the data produced. As such, it is important that all parties involved have a clear understanding of verification expectations, so that the process can be completed accordingly. **Reporting and verification** provide general insight on how verification occurs under the UNFCCC, as well as some lessons learned and recommendations.

The following processes within the integrated system are to be repeated for each measurement cycle, and in mature systems these processes present an opportunity to incorporate the **continuous improvement process** as part of the NFMS operation.

All the information should be stored and managed in an **information management system** which includes a database system, a processing system, quality assurance procedures, security and change management protocols, and a method for archiving and documenting the information. Such a system allows for consistency through the reporting period and transparent communication of the entire NFMS including data, processes, documentation and people.

Chapter 1 Institutional Arrangements

This chapter describes institutional arrangements which support effective MRV implementation, describing foundational, strategic and operational elements that an NFMS should have in order to enable a sustainable and effective MRV system. Like the 2019 Refinement(4), information presented in this chapter in non-prescriptive but rather suggests possible approaches to establishing arrangements that will improve quality, timeliness, and use of resources. This Chapter also presents guidance to countries for mapping their systems (**Section 1.4**) as a basis for defining, for instance, their institutional arrangements and capacity building needs. The MRV function of the NFMS under the UNFCCC is undertaken in the context of the International Consultation and Analysis (ICA) for the BURs and under the Technical Expert Review in the context of the Transparency Framework of the Paris Agreement for the BTRs (**Section 2.2**).

Implementation of national forest monitoring goals and reporting objectives, including those related to meeting Nationally Determined Contributions (NDCs) and reporting requirements under the UNFCCC, as well as other agreements and forums, require sound institutional arrangements (**Box 2**). The NFMS will be at the core of collecting and providing data on forest and forest change, but may also need to connect to other monitoring and reporting systems. In establishing institutional arrangements for an NFMS, as well as any linkages to other systems, consideration should be given to the range of requirements, mandates and jurisdictions that different National monitoring goals and reporting objectives may include.

Institutional arrangements and processes for an NFMS need to consider the requirements set out in decisions(5) of the Conference of the Parties (COP) to the UNFCCC related to REDD+ reporting requirements. For instance, the following elements need to be developed to enable access to REDD+ finance: (i) a national strategy or action plan; (ii) a National FREL/FRL; (iii) a robust and transparent NFMS(6) to meet MRV requirements for REDD+; and (iv) a system for providing information on safeguards(7) and results provided in a technical annex to a BUR.(8)

Well-established institutional arrangements that can deliver the MRV functions of an NFMS can strengthen the design and evaluation of policies and actions, consistent with sound forest policy and governance. This will increase transparency in reporting, facilitate financing where applicable, and lead to the quantification and reporting of mitigation actions in terms of emissions reductions and potentially other non-GHG impacts.

A sustainable operational NFMS enables the repeated assessment, evaluation, interpretation and reporting of data and the derivation of information that allows for the monitoring of change and trends over time (FAO, 2017). While there is no one size fits all approach when it comes to developing and operating an NFMS, there are basic **foundation**, **strategic** and **operational** elements that should be in place to enable an effective monitoring and MRV function. These elements may be developed taking into consideration basic overarching principles defined by the country. Regardless of the stage of the

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(4) **Volume 1, Chapter 1, of the 2019 Refinement** (IPCC, 2019) provides non-prescriptive guidance on GHG Inventory Arrangements including institutional arrangements, data sets and data flows, work plans, data management systems, management of QA/QC, training and education, awareness and public access to information. It is recommended to read through this material in combination with that presented in this Chapter.

(5) **Section 2.1** provides an extended summary of relevant COP decisions.

(6) Or subnational monitoring arrangements as an interim measure see **decision 1/CP.16, paragraph 71**.

(7) As specified in **decision 1/CP.16, paragraph 71**.

(8) The results should be submitted as an annex to the Biennial Update Report and verified in accordance with the modalities contained in **decision 14/CP.19**.

NFMS continuous improvement cycle (**Section 1.3.6**) consideration of a number of core principles related to governance, scope, design, data and overall operation can assist in setting priorities. These principles, while not being a prescription for an NFMS, constitute elements of common sense for a sustainable NFMS and may serve as a guide in NFMS development and improvement. A detailed description of these principles may be found in the **Voluntary Guidelines on National Forest Monitoring** (FAO, 2017).

Box 2: Institutional arrangements

Institutional arrangements(9) 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 information that can be used for policy relevant purposes.

The UNFCCC has published a **Toolkit**(10) for non-Annex I countries on establishing and maintaining institutional arrangements for preparing National Communications (NCs) and Biennial Update Reports (BURs). Though not specific to REDD+, the overall advice is relevant and important. These include that national institutional arrangements should help individual Parties to 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 national level.

In particular, institutional arrangements can assist Parties to:

1. Meet reporting requirements under the Convention;
2. Develop and build national capacities and ensure sustainability and consistency of reporting processes;
3. Inform national and international policymakers, at different levels; and
4. Assist in institutionalising activities relating to reporting on climate change.

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(9) **The UNDP website has a range of resources on advice and experiences of establishing institutional arrangements**.

(10) **The UNFCCC Toolkit for non-Annex I countries - establishing and maintaining institutional arrangements for a preparing national communications and biennial update reports**.

1.1 Foundation elements

Foundation elements of an NFMS ensure its long-term functioning in terms of timely delivery and quality of information collected, analysed and reported during repeated MRV phases (i.e. an operational system). Foundation elements can be grouped under three themes: (1) **institutionalisation**; (2) **developing national capacity**; and (3) **external partnerships and collaboration**. These themes are interlinked and some may be pursued simultaneously or using a step-by-step approach according to available resources, technological progress and capacity development with a view to establishing a sustainable operational system.

1.1.1 Institutionalisation

Institutional arrangements are most effective when all stakeholders are engaged early and effectively. Ideally, institutionalisation means that the NFMS is formally, firmly and permanently embedded within the national administration. The longevity of an NFMS requires a legal basis, financial commitment and a permanent institutional framework to ensure efficient implementation and operation. Only a permanently institutionalised NFMS can help to ensure that:

1. National monitoring of forests is considered an important government responsibility;
2. data and information are consistently collected, managed, made permanently available and analysed over time to enable assessment of changes;
3. the government has a clear focal point when analyses and specific forest information are needed;
4. National expertise is accumulated and further developed, which is a precondition for continuous improvement of the system; and
5. the expertise and experience developed is retained and creates the necessary institutional memory.

Opportunities and obstacles related to data accessibility and institutional arrangements are country-specific and so require tailored responses at appropriate levels. Given the interdisciplinary nature of REDD+ and other international reporting requirements, several government agencies, non-governmental organisations (NGOs) and institutions and community stakeholders may be involved. Even if a single institution is responsible for the NFMS, many actors need to be involved in the different components of the system, such as planning, data collection, Quality Assurance/Quality Control (QA/QC), data management, analysis and monitoring for reporting on forest-related status and trends and for verifying emissions reductions. Consequently, responsibilities for the different elements of the NFMS may lie with various institutions, or divisions and departments within them, or perhaps with experts outside the government.

Coordination requires clarification of each organisation's responsibilities within national institutional arrangements. Such coordination should facilitate both national and international reporting processes including, for instance, the preparation of FRLs, BURs, BTRs or National Communications to the UNFCCC. To facilitate this, an institutional body will be required to manage the work of institutions and organisations; it will have overall responsibility for the coordination of administrative and technical arrangements, the delivery of specific products and services, and the overall quality of reported estimates. Clearly designated, written roles and responsibilities (e.g. via Memoranda of Understanding (MOU)) for managing and monitoring REDD+ and GHGI emissions and removals will help to avoid confusion and assist in the 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. Also, the NFMS could collect data on other land uses, which might be used by other agencies for reporting purposes.

UNFCCC decisions suggest that a national focal point (or entity) be designated by the lead institutional body, and ideally be a member of the body. **Decision 10/CP.19** invites countries "to 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". Ideally, this national entity or focal point would have overall responsibility for coordinating the REDD+ MRV function and liaising with the UNFCCC, but it is important to note that this is not a requirement and that countries are invited to nominate a sole focal point. If the country decides to nominate a national focal point, this should be identified as soon as possible to avoid ambiguity among stakeholders concerning the role and responsibility of this lead person.

Mandates and MOUs are important to clarify roles, responsibilities, and accountabilities and to direct institutions to provide data or perform specific tasks. These arrangements should help to minimise difficulties in both human and financial resource allocation. The documents should specify how REDD+ institutions and stakeholders will work with those responsible for the NFMS implementation and national and international REDD+ and GHGIs reporting and with those who use the data for other management and policy purposes. While the strategic use of legal mandates is discussed in **Section 1.2.1**, desirable elements of an NFMS mandate include:

1. The vision, scope, goals and targets of the NFMS, which should be specific and measurable, covering both the short and long-term.
2. A clear designation of responsibilities and functions for all entities involved in achieving the objectives and targets of the NFMS, with normally a single principal coordinating entity.
3. If the NFMS is implemented in a decentralised manner, a principal entity needs to harmonise, coordinate and maintain consistency between decentralised entities.
4. Explicit commitments to impartiality, freedom from undue influence or potential conflicts of interest that may lead to biased and/or compromised results.
5. Specification of the means for implementing the NFMS, including resources (human, financial, infrastructure, etc.). The provision of funds via sustainable/appropriate finance mechanisms is critical to the implementation and continuation of the NFMS to provide up-to-date information at regular intervals. Using an annual survey design (**Section 3.2.1**) can help to stabilise funding and to retain institutional knowledge.

Rather than creating a whole new system, or one that is created solely with temporary donor project funds, it is efficient and more sustainable to integrate the NFMS and its activities (what will be done and produced, by whom, when, and with what resources, etc.) into existing national frameworks regarding policies and legislation, and into government structures (organisations) and financing systems (e.g. national budgets). For example, rather than creating different land use and land cover maps, coordinate with existing mapping agencies. It is also important to take into consideration lessons learned from previous/existing experiences of national institutionalisation processes, and possibly relevant cases from outside the country (**Box 3**). In the context of both GHGIs and REDD+ MRV requirements, data-sharing agreements (**Section 1.3.2**) have been used by some countries and institutions, often as an interim solution before comprehensive NFMS institutional arrangements are established. 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 **Section 2.5.2.1**.

Box 3: Country experience in effective institutionalisation

As part of the development of the REDD+ framework, Madagascar created the National Office of REDD+ Coordination (BNCR), which had the mandate to develop and implement the REDD+ Strategy. At the time the mandate to report to the UNFCCC and compile the National GHG Inventory belonged to the National Office on Carbon and Climate Change Coordination. The Directorate of Forests has the legal mandate to monitor forests and it is in charge of international communications on forests. These agencies are part of the Ministry of Environment and Forests. In order to clarify competencies in terms of MRV function for REDD+, the BNCR hired a consultant to conduct a mapping of the system, evaluation of legal mandates and roles and responsibilities. After a public consultation with relevant agencies it made a proposal. The two coordination offices were merged, which ensured that one entity would be mandated to report on all UNFCCC processes. An MRV unit within the resulting coordination office is now in charge of compiling the GHGI for the forestry sector, including REDD+, and liaises with the relevant agencies for estimating forest cover change information. The Nationally Determined Contribution and future national GHGI will be updated based on the FREL submitted to the UNFCCC, which in turn is based on forest information generated as part of the NFMS being implemented by Madagascar. These competences and mandates have been incorporated into a presidential decree that will be approved in the near future.

1.1.2 Developing capacity

Capacity development should be an integral part of ensuring effective operation of an NFMS and associated reporting systems. Capacity development should be closely integrated with the NFMS planning and operational processes. Although capacity development should strive towards **continuous improvement**, it is not necessarily a linear process and should also include **regular assessment** and be adaptive to changing needs, methodologies, and institutional organisation.

FAO (2017) provides broad guidance for developing national capacity for an NFMS. Meeting climate relevant reporting requirements should include additional consideration of arrangements with institutions and stakeholders who are core to climate reporting, but who may not be familiar with NFMS requirements. There is also a need to ensure harmonisation with programs engaged in other elements of land sector accounting (e.g. Agriculture). Capacity building plans should therefore consider addressing needs beyond those specifically linked to the NFMS.

The development of 1-2 year plans that describe needs and arrangements for building capacity (who, when, how) should consider the following:

1. Capacity building should be integrated into a regular planning and assessment process (**Section 1.3.1**) to allow the simultaneous tracking of forest monitoring and reporting implementation and identification of areas for improvement. These needs may be identified together with a system evaluation (**Section 1.4**).
2. Carefully consider where specific technical capacity may be best met by external sources from either the academic or private sectors (**Section 1.1.3**). In these cases, it may be important to ensure that the capacity to manage and oversee contracts exists in the relevant institutions.
3. Consider not only technical capacity, but also administrative and managerial needs. Likewise, both the short term and long term requirements should be considered.
4. Consider where there may be opportunities for cross-institutional training, allowing teams or units that will need to work collaboratively across institutions (e.g. to share data or analytical platforms) to interact and gain shared understanding.
5. Ensure maintained/accumulated capacity in relevant institutions either ensuring through some redundancy (e.g. multiple persons are working in the same function) so that when people leave the capacity is not lost, or setting up ways to create/retain institutional memory (e.g. creating

tutorials, documenting processes, repeating training for new staff).

6. Effective internal communication can help to build capacity across all aspects of the NFMS from institutional arrangements, technical capacity and administrative and managerial needs.

Capacity needs assessment and planning process may follow the following steps:

1. Conduct a comprehensive, systems-based assessment process to identify responsible positions and institutions for current NFMS and associated reporting as well as future needs. (**Section 1.4**).
2. Develop an initial institutional arrangements plan.
3. Identify existing and expected future capacity gaps.
4. Develop capacity building plan to ensure that current capacity can be maintained and that future capacity building needs will be met.
5. Share capacity building plan with relevant institutions and partners to get feedback and identify possible collaborations on capacity building. Communication and dissemination may follow.
6. Work with relevant national decision makers and external funding sources to determine how to implement and find financial and technical recourse for capacity building plan.
7. Regularly review capacity building plan to track progress and identify new or changing needs as NFMS and reporting evolves.
8. Conduct regular assessment of progress, needs and status of institutional arrangements (returning to Step 1).

1.1.3 External partnerships and collaboration

External partnerships can be an important and ongoing part of an operational NFMS and can enhance any operational structure (**Box 4**) established as part of the **institutionalisation process**. External partners can include national government departments outside the nominated NFMS structure, non-government agencies, industry, national and international experts, international partners or other countries through South-South collaboration. Some examples of how external partnerships can be structured are presented in **Box 5**.

Establishing formal and informal external partnerships can help to overcome some of the limitations of internal resources and capacities (**Box 5**). Often, joint working starts informally and can be very productive. However, informal arrangements can become problematic if anything goes wrong. As joint working develops, it is important to ensure that there are appropriate arrangements for governance and management. This could include establishing a letter of intent, an MOU or a contract.(11)

Typical examples of the type of situation in which an organisation may enter into a MOU (**Box 6**) that is not intended to be legally binding are:

- to record an understanding between two or more agencies to identify programs and target groups for the delivery of programs to joint clients;
- to promote cooperation and further develop a positive relationship between two agencies and to encourage interaction between respective staff, including inter-agency meetings, publications

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(11) An MOU is intended to formalise the terms of a relationship, arrangement or understanding between the parties, but is not intended to be legally binding on them, as opposed to a contract, which is a legally binding promise or agreement.

and client service collaboration.

Partnerships can provide a platform for new knowledge. Through shared decision making, execution of collaborative tasks, mutual interdependence and problem solving, each party to the partnership can learn with and from each other ultimately resulting in an improvement of the NFMS **operational functions**. This is best achieved through strategic partnerships where:

- agreed responsibilities and accountability are clear among all partners;
- objectives are aligned;
- the aim is to be collaborative, not competitive;
- duplication of effort is avoided; and
- all parties have a general understanding of the work that will be conducted.

It is common to progress from informal to more formal partnerships as the NFMS matures. Adopting this more formal approach to engaging with partners will assist in coordinating the many different partnerships typically established in support of NFMS development and operation, and will avoid duplication as much as possible. The four stages of building mature formal collaborative partnerships are:

1. **Exploration**
    - Understand NFMS needs.
    - Investigate who is best placed to fill the needs.
2. **Formation**
    - Collaboration practices are defined, agreed and documented.
    - A common outcome from the collaboration is articulated.
    - Mutually reinforcing or joint strategies are established.
    - Compatible policies, procedures and other means to operate across agency boundaries are established.
3. **Operation**
    - Roles, responsibilities and resources are agreed.
    - Needs identified in the exploration phase are achieved by leveraging all available resources.
4. **Evaluation**
    - Mechanisms to monitor, evaluate, and report on results of the collaboration are developed.
    - Findings from evaluation of collaboration informs the NFMS **continuous improvement processes**.

The involvement of research and academic institutions as well as the private sector will ensure long term sustainability of the NFMS through several factors. Planning and successful long-term implementation of an NFMS and its associated MRV function requires accompanying research and development in all cases, although to a varying degree (FAO, 2017). Relationships to research organisations and the private sector can therefore be key to the development and sustainability of an NFMS.

Firstly, research and academic institutions and local consultancy firms can play an active role in the development and implementation of the NFMS through research and testing of improvements to the NFMS to solve challenging issues. Secondly, these relationships can provide local and national expertise, leading to a strengthening of national capacity and ensuring longer term sustainability. Thirdly, data generated from monitoring also informs research. Data from national forest monitoring efforts are increasingly used in research projects and are crucial inputs for informing decisions on national forest policy. In addition, the data generated by an NFMS offer manifold opportunities for research beyond the specific field of forest monitoring.

National and international research and academic institutions established within the country should be considered as stakeholders in the design and implementation of an NFMS, and at the same time potential users of the NFMS once it is established. To a large extent, this also applies to the private sector and civil society organisations, which in the field of forest monitoring often have close ties with national research organisations.

There is a close relationship between the strengthening of forest monitoring-related research and capacity building. However, to be effective, the relationship(s) need(s) to be formalised. This can be done mainly at two levels:

1. At institutional or strategic level for which a formal relationship is established between the mandated institution and the relevant research institution, through a legally binding link such as an MOU.
2. At operational level, through specific public procurement.

The identification of priorities for forestry research and development will itself require developing sufficient capacity to ensure that it is based on stakeholder needs. In addition, strengthening research institutions will help to (FAO, 2017):

1. Ensure that the flow of information between the NFMS and its MRV function and researchers is reciprocal: research objectives should be clearly defined by the NFMS, but flexible enough to permit the incorporation of new research results and improvements to the NFMS.
2. Identify scientific research needs to fill existing information gaps, specifying research priorities and providing certain basic facilities to facilitate progress, enabling the researcher to lead the NFMS into new areas of development.
3. Promote collaboration with different research units, where possible, with the goal of enhancing implementation and fostering sustainability of the NFMS. In this context, research collaboration with universities can encourage young scientists to become interested or even enthusiastic about forest monitoring.
4. Promote networking and collaboration among national, regional and international research institutions and actors, to ensure adequate channels for the dissemination of results.

Box 4: Examples of NFMS operational structures and types of partnerships

- **Centralised vs. decentralised -** The country's lead agency may maintain most control and decision-making authority. A centralised approach will probably include relatively few other institutions. By contrast a decentralised approach may include many different teams and/or institutions with different roles, responsibilities and available resources. Countries with a large administration and various institutions with relevant expertise are more likely to use the decentralised approach. In this case, it is important to identify the lead agency that will have an essential coordinating role, to ensure consistency between methodological decisions made by different teams and/or institutions involved. Arrangements for enhancing cooperation with subnational jurisdictional institutions that monitor at a subnational level should be explored.

- **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 the development of capacity of NFMS agencies, with the aim of maintaining consistency and sustainability over time, particularly in respect of managing out-sourced resources while 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. A multi-agency structure requires clear delineation of roles and responsibilities (typically based on agency mandates), to ensure that there is a clear line of decision-making and reporting 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.

Source: Hewson *et al.* (2014).

Box 5: Partnership and Collaboration in Fiji's National Forest Monitoring System

Fiji has adopted a centralised approach to the operation of its NFMS. The Ministry of Finance is the lead agency and national UNFCCC focal point, including for REDD+. The Ministry of Finance relies on the Ministry of Forestry for forestry related information to meet its UNFCCC reporting obligations. As such, the Ministry of Forestry is responsible for the NFMS.

The Ministry of Forestry established a multiagency approach to guide NFMS design and operational decision making. The REDD+ Steering Committee consists of representatives from 15 government and non-governmental organisations, each with clearly defined responsibilities related to representing the interests of its stakeholder groups and contributing technical expertise specific to its focus areas.

Where possible, the Ministry of Forestry prioritises in-sourcing the operation of the NFMS. To build the required capacity and infrastructure, a number of short term consultancies have been undertaken including: advice on appropriate methodologies to meet design decisions; in-house capacity building related to data processing and data analysis; establishment of appropriate laboratories and other infrastructure; and documentation of system processes. As a result of these short-term consultancies; the Ministry of Forestry can competently generate annual forest cover and forest cover change data (activity data) in-house and have the required database and integration tool capable of generating REDD+ emissions removals estimates to the Ministry of Finance for external reporting requirements.

The following lessons have been learnt from this phase of initial out-sourcing:

- Requiring out-sourced contracts to include deliverable that build capacity building and provide system documentation, such as standard operating procedures, assists in establishing the required foundation for in-sourced capacity.
- Commitment to financial resources for infrastructure and additional targeted training was found to be effective in operationalising in-sourced capacity within the Ministry of Finance.
- Internal and external partnerships, such as those established through the REDD+ Steering Committee and World Bank Technical Support Unit, are important support structures for staff as capacity and confidence grows.
- Sharing experiences with other agencies and countries can further strengthen capacity and confidence.

Box 6: Example of information that could be included in a Memorandum of Understanding

As a general rule, a Memorandum of Understanding (MOU) would include:

- Details of the parties to the document (Named individuals who can make decisions or speak on behalf of the agency in relation to the MOU and provision of the services specified therein)
- Background
- Objectives, purposes and anticipated benefits
- Agreed actions/services
- Operational and implementation arrangements.

In addition, where two or more agencies are, for example, sharing an income and or participating in joint research, the following may be considered depending on the local regulations:

- Payment arrangements
- Intellectual property arrangements
- Financial and/or resourcing arrangements
- Conflict resolution mechanisms
- Risk management (such as exclusions or limitation of liability, insurance requirements and indemnities).

Each MOU should include a statement of understanding (i.e. an express statement to the effect that the MOU is not intended to create legally binding obligations on the parties). Generally speaking, an MOU would not include information about expiry or termination dates, though it should specify a date of review.

A copy of the MOU signed by an executive officer and/or Chairperson (or equivalents) should be kept by each of agencies involved in the participation and the signing off of the MOU. In the case of an agency developing a number of MOUs with multiple agencies, it may be advisable to create a reference for each MOU, comprising:

- Reference number
- Names of the party/ies involved
- MOU contact name, position and details
- Description of the objectives of the agreement and actions to be undertaken by our agency
- Period of the document, including review and extension options
- Specified outcome/s (optional)
- Letters of termination or extension.

1.2 Strategic elements

Strategic elements refer to organisational and planning actions for MRV activities within a National Forest Monitoring System, including: the **mandate**, **identification of information needs and stakeholders**, **communication and dissemination**, and **effective use of resources**.

1.2.1 Mandate

The implementation of an NFMS requires a clear political mandate, which can only be issued by a government body. Mandates also usually imply the definition of a vision, goals and targets and the specification of available resources, including budget, personnel and infrastructure. In some cases, legal regulations are also necessary, for example, to facilitate access to private land to conduct field inventories. Strategically, mandates are important for several reasons, many of which were mentioned in **Section 1.1.1**. Formalisation of expectations and responsibilities can provide an enabling operational environment for stakeholders.

Developing a mandate is typically a political process which helps to bring together the organisations that will utilise the NFMS information, such as environmental agencies and non-governmental groups, forest and related industry, universities, civil society and international bodies. The broader the support, the more likely the government will be to create the necessary mandate.

Often, different agencies have related or overlapping mandates, such as the agriculture department having authority for conducting the National Forest Inventory, the geological department for national maps, and the environmental protection department for national and international reporting for REDD+ and GHGIs. Unfortunately, this can lead to conflicts, delays, and missing information. The institutional body must work with each of these organisations to create an agreement that addresses these issues. Where mandates overlap or leave gaps, the institutional body and member organisations need to work together to amend the mandates so as to address the challenges.

1.2.2 Identification of information needs and stakeholders

Identifying and considering all international and national reporting requirements and the stakeholders involved with these processes can improve the long term sustainability of the system. The establishment of the MRV function of an NFMS for greenhouse gas emissions from the forest sector requires a clear mandate from the government. Once the organisation(s) with such a mandate has/have been identified, it is then necessary to define the expected results and outcome from the system. This process should start by considering the international(12) and national policy requirements and related information needs. These information needs are likely to be present in different organisations and levels within them, so a second round of information gathering may be required after identification of other relevant stakeholders, which will feed and make use of the information generated.

Identifying stakeholders can be an iterative process, through various stakeholder consultations. There are different types of stakeholder consultations that can be implemented, depending on the expected outcome. If little information is available on existing stakeholders and needs, an online or postal survey can be a good source, but the return rate tends to be very low and should be at least followed up with semi-structured interviews, in which the survey is used as a guide. Once most stakeholders are identified, organising a series of workshops in which the stakeholders identified are invited

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(12) UNFCCC reporting requirements are outlined in **Chapter 6**.

can represent an efficient way to gather information needs. However, this process should be well structured, with clearly identified activities and outcomes to ensure that it is completed in a timely manner.

The information needs can then be explored in detail and summarised by stakeholder groups. Typically, stakeholders can be grouped into the following categories:

- **Governmental institutions -** represented by their implementing institutions and partners, who are predominantly users of a service or result, but can also be producers of capacities. Country users primarily have to report according to UNFCCC requirements (e.g. REDD+), but also need information related to national policy development (i.e. for NDCs) and implementation, including the production of forest management plans. This includes subnational jurisdictional governments that have forest management authority.
- **Financiers -** donors and international development agencies supporting the implementation of REDD+ and climate smart and sustainable land use where forests play a major role. Donors are users of forest information and are also active in the technical implementation of NFMSs and their associated MRV functions and UNFCCC processes. Further, they are important Stakeholders for the technical and financial support of NFMSs.
- **The research and scientific community -** act as both users and producers (i.e. developing the methodological underpinnings and ensuring the quality of the output from such a system).
- **Civil Society Organisations (CSOs) -** are using forest data to fulfil their role as independent watchdog organisations and as advocacy and implementing bodies. To some extent, CSOs can be producers of capacities to contribute to such a system.
- **Private sector organisations -** are also both users and producers of capacities. Private sector institutions can be those managing forest concessions or consultancy companies providing services to the forest sector and / or from earth observation.

Undertaking a review of the current system as part of targeted stakeholder workshops can assist in identifying the current capacities, and performing a gap analysis can identify priorities and pinpoint where the efforts should be concentrated (**Section 1.4**). Completing this review process facilitates the structured, comparable monitoring and evaluation of progress towards implementation of an operational, mature and effective NFMS.

1.2.3 Effective use of resources

Establishing and maintaining an NFMS requires significant upfront and ongoing commitment and resources. When well designed, an NFMS can support a number of national and international reporting opportunities. Countries and international agencies should consider the most effective use of human and financial resources to deliver multiple required MRV functions. This entails considerations such as:

- which pools and activities are likely to be significant in determining the level and trend in emissions and removals;
- the availability and cost of remotely sensed data;
- the need for pre-processing and associated costs;
- the assessment of existing data sources and the costs associated with acquiring and processing new sources of data;
- the existence of ground-based data sets and the need for new or supplementary surveys;
- the 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 (e.g. Forest Resource Assessment) or improving management of resources that will facilitate the flow of information, co-ordination of different institutions and 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 so MRV processes need to be designed to serve known current and future policy requirements, they are also conditional on technical capabilities, initial development and operational costs (Böttcher *et al.*, 2009; Maniatis *et al.*, 2019).

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:

- MRV functions should be considered as a long term program, not a project, and will need to be internalised in the regular operations of institutions.
- MRV design should be based on policy and reporting needs, country specific circumstances and definitions, financing mechanisms, available technology and prospects for results-based payments. This will require close collaboration between policy makers and technical officers.
- The evolution of annual budgets through all phases of the program should be considered from the outset as part of the design and implementation stage, to help ensure that the program can be adequately funded.
- Sources of funding are 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 most

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 through a one data platform policy should be considered as a way to seek cost efficiency and long term sustainability.

The cost effectiveness of an MRV program design will depend on the balance between MRV and other costs and the benefits of participating in UNFCCC processes, such as REDD+, as well as the possibilities for using the NFMS 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 land use management beyond forests (Böttcher *et al.*, 2009). If the monitoring costs associated with co-benefits in other sectors such as optimised 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.

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.

1.2.4 Communication and dissemination

Communication and dissemination are critical elements to ensure the sustainability of the National Forest Monitoring System, as it facilitates access for relevant stakeholders, including decision makers, to the wealth of information being generated and creates awareness of the efforts being made and the needs. It is not uncommon to see gigantic efforts by governments to collect data and estimate the status of natural resources, only for these to have very limited impact due to lack of internal and external communication. Moreover, donor governments that could further support the forest monitoring system receive very little information on the real progress made by countries, giving them the impression of lack of progress, and do not receive information on the existing gaps.

Communication and dissemination should target both internal (e.g. government agencies) and external stakeholders (e.g. universities, civil society, donor governments), and should be defined in written form in a communication and dissemination plan that is managed and led by a person assigned to this role. The communication and dissemination plan is a simple document that generally specifies the objectives of the plan (i.e. key questions to be answered), target groups, the tools for dissemination and their linkages to each target group (e.g. social media, website, scientific publications, newsletters), monitoring and evaluation to track progress, planning (i.e. activities and timing), and roles and responsibilities for each activity. In the age of information technologies, communication and dissemination is much more efficient and less costly, so should rely on these means. Several people can be targeted through a website or blog and social media can be used to effectively reaching more people. One example of dissemination using websites is in Mozambique (**Box 7**). Additional actions for efficient dissemination and communication are provided in the Voluntary Guidelines for National Forest Monitoring (FAO, 2017).

Communication and dissemination should not only cover results and methods, but also information on capacity needs and existing gaps. Internal and external stakeholders should also understand the needs of the National Forest Monitoring System so that adequate support may be provided. This has to go hand-in-hand with evidence of results from the NFMS so that government decision makers and country donors are more open to providing further support.

Communication and dissemination should take as a reference the principle of transparency which is key for ensuring the credibility of the reported results provided by an NFMS. Transparency is good practice in inventory development; multiple UNFCCC processes aim to increase transparency of submissions and mitigation actions and effects, but it should also be considered in the development and implementation of communication and dissemination strategies.

Box 7: Mozambique - Example of communication, dissemination and data sharing

One example of good dissemination and data sharing is that of Mozambique. A specific website on MRV(13) provides access to relevant data and results and provides updated information on the activities being conducted. Websites such as this one may be created with any free web page builder that can be found on the internet; this specific website was created by the MRV unit. In addition, a geoportal and dashboard(14) enables easy access and free downloading of all geographical information and data, including estimates of NFI plots, historical deforestation data, the 2016 land use and land cover map and annual deforestation maps by province. In this case, all data may be accessed by users except for the tree data of the NFI, which have to be accessed through a specific form on the website. These are powerful visual dissemination and communication tools that may be easily shared with internal and external stakeholders. Mozambique is an example of a fully transparent data policy, which was defined after discussions with the Ministry in charge of public data policies. Countries are encouraged to discuss with their relevant ministries before defining their data policies.

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(13) **www.fnds.gov.mz/mrv/**

(14) **https://www.arcgis.com/apps/webappviewer/index.html?id=1e201cf974584b38ac5dd92b005c99ae**

1.3 Operational elements

Operational elements refer to actions for the definition and optimisation of a framework for **information management**, **system processes**, **infrastructure**, **documentation** and the supporting system qualities of **quality assurance/quality control** and **continuous improvement**.

1.3.1 Processes

An NFMS comprises components and processes (**Figure 1**), both of which should be established with identified **monitoring goals** in mind. Processes represent all the things that need to be done in order to make the system operational. These rely on inputs, such as data or human resources to produce outputs, such as data or reports. Processes should be established that take into consideration **mandates**, roles and responsibilities and **technical design decisions** established to meet defined monitoring goals. Common processes related to an NFMS can be categorised as establishment processes and operational processes.

Establishment processes ensure that the following foundational and strategic elements are taken care of and documented:

- **Design -** The design addresses the objectives of the monitoring system, what will be monitored, how the data will be used, what indicators will be prepared, and how stakeholders will be involved. The geographic and temporal details have been determined for example, frequency, timing, location of monitoring.
- **Implementation -** The parties responsible for each aspect of the system have been identified and have received the necessary training. The methods and sampling strategies have been tested and documented. Contingency plans are in place to respond to problems. Important processes related to implementation are those that are repeated.

Operational processes are typically repeated across the monitoring period defined in the design phase and can be categorised as a range of activities, such as:

- **Data collection -** Procedures and practices to obtain the data are established and applied. The samples and data records are documented and archived.
- **Quality control -** The methods are consistently applied, following guidelines and standards. Other quality controls are in place to maintain the integrity of the data sets.
- **Data processing and analysis of the data -** The data are converted into forms ready for reporting. Indicators are calculated and used to compare results to those for other times and locations, using statistically sound methods.
- **Internal reporting and communication -** The results are communicated within the organisations responsible for monitoring. The data are available internally, with a description of their properties and limitations.
- **External reporting and communication -** The results are communicated to external audiences (the public, Parliament, or international bodies, such as the secretariats responsible for international agreements). Specialised users have access to detailed monitoring results.
- **Review of the system -** Evaluations of the monitoring system are conducted to assess whether it is achieving its objectives, and to identify opportunities for improvements.

Process documentation is used as a NFMS process guide for compilers, decision makers and internal/ external stakeholders. Such documentation should provide a detailed description of how each process in the NFMS is carried out and can include all types of document that support a process, such as:

- policies
- checklists
- tutorials
- forms
- screenshots
- links to other applications
- process maps

Documenting each NFMS process will help to:

- **improve processes -** documenting the exact processes can help to identify bottlenecks and inefficiencies;
- **train employees -** process documents can help new employees to understand their job roles and familiarise themselves with the processes in which they will be involved. Experienced employees can also refer to these documents as necessary to ensure that they are executing the process correctly;
- **preserve knowledge -** keeping a record of processes known only to a few people specialised in conducting them will help any newcomers to resume the work easily;
- **mitigate risks -** and maintain operational consistency; and
- **make it easier -** to outsource work or automate processes.

Using a step-by-step method to document a process will help to execute it more efficiently.

Step 1: Identify and Name the Process - Determine its purpose (e.g. why and how the process will benefit the organisation) and provide a brief description.

Step 2: Define the Process Scope - Provide a brief description of what is included in the process and what is beyond the process scope, or what is not included in it.

Step 3: Explain the Process Boundaries - Where does the process begin and end? What causes it to start? And how do you know when it's done? Get these boundaries well defined.

Step 4: Identify the Process Outputs - Establish what will be produced by the process or what result the process will achieve once it is completed.

Step 5: Identify the Process Inputs - List the resources necessary to carry out each of the process steps.

Step 6: Brainstorm the Process Steps - Gather all information on process steps from start to finish. Either start with what triggers the process or start at the end of the process and track back through the steps to the starting point. The brainstorming session should involve those who are directly responsible for the process tasks or someone with extensive knowledge of it, as they can provide precise data.

Step 7: Organise the Steps Sequentially - Take the list of steps you have compiled and put them in a sequential order to create a process flow. Keep the number of steps to a minimum and if a step includes more than one task, list these under the main step.

Step 8: Describe who is Involved - Decide each individual who will be responsible for the process tasks. Define their roles. Mention the job title rather than personal names. Also be considerate about those who would be referencing the document. Write it in a way that any employee with a reasonable knowledge can read and understand it.

Step 9: Visualise the Process - This is to improve the clarity and readability of your documentation. Using a process flowchart, neatly visualise the process steps that you identified earlier.

Step 10: Note any exceptions to the normal process flow - A process may not always follow the same flow due to various reasons. Mention these exceptions and what steps will be taken to address them.

Step 11: Add Control Points and Measurements - Identify where risks could occur in the process and add control points to help the process owner when monitoring the process. Establish measurements to determine the effectiveness of the process and to help improve it.

Step 12: Review and Test the Process - Gather everyone involved and review the process flowchart you have mapped. Are there any missing steps? Is everything in order? Once done, test the process and see if you have missed anything.

When documenting processes consider the following:

- Keep the document simple and concise. While it should be technically accurate, it should be easy to follow.
- Have a proper plan in place to update the documents when/if the process should change. Be sure to review them at least once a year. Or assign a process owner who can do regular reviews and notify others of the changes.
- Keep separate documentation for every different process to avoid confusion.
- When documenting processes for the first time, avoid covering the entire organisation at once. Start from a single process within a department, or a major process common to the entire organisation.
- Store the documents in a location that is easily accessible by anyone who is looking for it. Consider storing documents online in a central location via a process documentation tool.
- Make sure that it is easy to be revised when needed and the new version can easily be distributed to everyone involved.
- Use appropriate examples, graphics, color coding, screenshots, multiple platforms etc. as necessary.
- Ensure that the process documentation complies with the existing standards of your organisation where they exist.
- Create a process documentation guide, which anyone can refer to as a standard template for documenting a process.
- Make use of existing documentary material, records, interviews, case studies, field-diaries of project staff and the knowledge of employees to gather information for process documentation.

1.3.2 Information management

Information management facilitates access to the NFMS data sets (or sub-sets) and requires the following management processes to facilitate consistency and transparency in reporting:

- Data archiving
- Data privacy, copyright and intellectual property rights

- Data documentation and metadata
- File formats and data types
- Data version control
- Data security and encryption
- Data storage and backups

An operational information management system relies on effective institutional arrangements and associated agreements and processes, in particular: (i) data sharing policies; ii) database structures (software) and physical databases; (iii) database experts with access to data and metadata; and (iv) institution(s) where the database and experts are located.

NFMS information, including raw and processed data, may be of interest to many parties and should be accessible to different users, either as original or aggregated data sets. This does not necessarily mean that open public access is granted for all data available, but rather that a clear data sharing policy is formulated, to which national and international interested parties can refer. This policy may contain restrictions in line with national interests and legislation, such as restriction to plot locations to avoid access.

Early attention to information management is a critical step in ensuring that estimates can be reproduced and safeguarded against data and information loss, and that data can be managed and maintained over the long term. Data sets, and their metadata, require storage in ways that promote: (1) access as data needs change; (2) reprocessing as errors are discovered and calibration is improved; (3) recalculation as new data products, algorithms and data technologies are developed; and (4) user-friendly access.

Effective documentation and archiving serve as institutional memory and should store:

- not only final data but also source data that was used for estimating algorithms, models, etc.; and
- information with enough detail to support new teams or team members in their roles.

Where possible, all information should be stored in a central location and ideally the NFMS will have a multipurpose function to reduce duplication of work and make efficient use of resources.

Responsibility for the operation and maintenance of the information system should be **institutionalised**. Operational processes should be **documented** outlining, for example, 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 confidential data, such as information about landowners or residents.

The system need not be expensive or complicated and may be digital and/or print based; it should be located in a specified location, central to the NFMS. There are a number of sources available to assist in developing information systems. The **ISO quality management and environmental management standard** outlines a useful framework which can be built on over time.

Recommendations for an effective information management system include the following:

1. Incorporate comprehensive information management into the design of an NFMS from the outset. Provision needs to be made for long-term information management, to allow analyses to be repeated and time series to be built from inventories at earlier points in time.
2. Establish a well-documented data set with associated metadata (e.g. model coefficients and references, sample design and plot configuration), a complete and well defined protocol for data archiving and preservation including storage and backup, and a long-term vision to ensure

that data storage technologies remain up-to-date and data remains retrievable in the event that operating systems and data storage systems change.

3. Include a security protocol with a description of technical and procedural protections for information, including confidential information, and details of how permissions, restrictions and embargoes will be enforced.
4. Define a data policy that describes which data may be shared and how (e.g. free and available, available upon request, restricted) including access procedures, embargo periods (if any), technical mechanisms for dissemination and exchange formats. In cases where some parts of a data set cannot be shared, the reasons for this should be specified (e.g. ethical, personal data rules, intellectual property, commercial, privacy related, security-related). Consider restricting the dissemination of actual coordinates to the analysts concerned, or only making aggregated data publicly accessible. This decision regarding which data sets to make publicly accessible, and which to should have more restricted access, is dependent on national legislation, strategies and policies.
5. Define how and where data will be stored, indicating in particular the type of repository (e.g. institutional, standard repository for the discipline, etc.) and the institution(s) responsible for storing and archiving the data.
6. Establish, document and employ standards for data content, classifications and technologies used in data collection and generation.
7. Determine/design the data collection software and compatible hardware needed, especially if using portable data recorders.
8. Ensure that personnel are not only able to complete tasks regarding data collection, entry and analysis, but also able to update or modify databases when necessary.
9. Document the estimation methods and models chosen with related statistical model formulas and the computer code used.

1.3.3 Infrastructure

An operational NFMS requires both capital and operational expenditure on infrastructure and physical equipment, combined with appropriate building infrastructure within which to store and operate the equipment. The types of expenditure also depend on the governance and **institutional arrangements**. For example, it is possible that the organisation responsible for developing emissions estimates will not be the one responsible for collecting forest inventory data or calculating emissions factors or stock changes. This may also be separate to the agency responsible for collecting remotely sensed data. In these cases, infrastructure is still required, but its management is the responsibility of different entities. There is no one model. Some examples of infrastructure costs and issues common to NFMS are listed below.

Building Infrastructure

Building infrastructure is the most obvious but commonly overlooked aspect of an NFMS. It can have long-term implications. Moving offices within government is typically a long and drawn out process and commercial office leases are often relatively long-term (e.g. three years or more). Office fit-outs can cost more than rent. As such, the following issues should be considered, noting that expert advice on office set-up and arrangements prior to entering any long-term arrangement can be beneficial.

- **Security issues -** security needs to address personnel, data and asset protection. Data security is often overlooked, as much of the data being held by the NFMS may be public. However, there are numerous issues around access to some data (e.g. that held under specific licences or confidentiality agreements) that need to be managed appropriately. Physical assets also need to be secured, meaning that the building may have different areas with different levels of access.
- **Size -** apart from being able to house all staff, the building needs to have sufficient space and dedicated rooms for equipment, etc.
- **Heating and cooling -** both for staff and equipment, in particular air conditioning for servers and other computer equipment.
- **Reliable electricity connection -** this will be particularly important where the NFMS has significant hardware infrastructure. Consider buildings with an in-built Uninterruptible Power Supply.
- **Internet connections -** Where cloud-based services are used, a stable, fast internet connection is required, ideally linked to key machines using physical cables rather than Wi-Fi connections.

Hardware and Software

The NFMS will require some computing hardware and software to process, view and/or store raw and processed data. Traditionally, systems for storing and processing remotely sensed data and forest inventory data, and running more sophisticated analyses and systems required dedicated computer resources, such as servers and large storage systems. These days, the amount of physical hardware required depends on the system design and how much countries can, or are willing to, use cloud-based services (**Box 8**). In addition to physical infrastructure, many organisations are moving towards virtual systems, in particular cloud-based storage, processing and software systems. The exact mix of physical and virtual infrastructure will vary depending on country circumstances, including, but not limited to, system requirements driven by **technical design decisions**, **internal capacity**, government policy, security and financial resources. Cloud-based services can have advantages including reduced total running costs, greater security, increased speed and reliability and comprehensive data backup and recovery.

However, it is currently not possible to completely replace all hardware requirements of the NFMS with cloud systems as it fully relies on a stable internet connection, so careful consideration of these risks is needed. At a minimum, basic hardware, such as laptops and workstations, will be required. Where a country wishes to do more advanced processing, it may need to consider larger servers with a significant central processing unit (CPU) to store, process and share all geospatial information. Systems are also needed to store and update non-geospatial data and NFMS documentation including instructional manuals, standard operating procedures and tutorials. Separate servers may be required to host a web-portal and registries. In all cases countries will need to consider backup systems, failovers and other redundancies, all of which can become costly and require building infrastructure.

Software is required for a range of computing requirements including operating servers, cataloguing data, processing, and analysing data. An NFMS will probably use dozens of different software packages, from program management software to statistical packages to geographic information systems (GIS) and integration tools.

There are three general categories of software; proprietary(15), open-access and open-source(16). Proprietary software is primarily commercial software that can be bought, leased or licensed from its vendor/developer. Open-access software is freely available (sometimes under certain conditions or licences) but the source code is not available. Open-source software is where the code is freely available under certain license conditions and where, in some cases, the code is compiled ready for use (like open-access).

Few software packages are truly cost free(17). Proprietary software generally has a set cost that includes use of the software, support, training and updates. Open-access packages often have less direct support, which may require the hiring of consultants or other experts to run them. Open-source packages are similar to open-access, but may also require the hiring of developers to compile and install the software. All software has licence conditions for its use and/or modification. These conditions need to be clearly understood, as they can have significant implications for those countries producing new intellectual property on top of existing systems.

Within these general categories of software there are also two main pricing structures: purchasing or subscribing. Purchasing software can be expensive upfront, but can provide ongoing use without any additional costs. However, the user is typically required to pay for new versions as updates are released. The development of cloud services has led to a rapid shift to subscription type services. These services make available storage and processing capacity and can therefore also reduce hardware costs. More and more software is also moving to subscription-based services. Subscription costs typically require a lower initial outlay compared with purchasing software, but if there are a large number of users or storage, the total long term cost may end up higher than purchasing software outright.

When choosing software packages, costs should only be one consideration. Even if there is no capital expenditure for software (i.e. open-source or open-access software is preferred), operational budgets for software-as-a-service costs and any associated training/capacity building in its use should be

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(15) Proprietary software, also known as closed-source software, is software for which the software's publisher or another person retains intellectual property rights-usually copyright of the source code, but sometimes patent rights.

(16) Open-source products include permission to use the source code, design documents, or content of the product. It most commonly refers to the **open-source model**, in which **open-source software** or other products are released under an **open-source licence** as part of the **open-source-software movement**. Open-source is not necessarily cost free but rather it's a decentralised model that encourages open collaboration. Users can usually download the software and use it free of charge and contribute to its development through changes to meet their specific needs. Should a user require support or tailoring of the open-source software, many programmers provide software services and support. This way, their software remains open and free of charge, but there is a fee for providing support (if requested) to install, tailor, use, and troubleshoot it.

(17) **Open Foris** is an FAO-led initiative to develop, share and support free and open-source software tools to implement multi-purpose forest inventories and forest monitoring. The main components are Collect, Collect Mobile, Collect Earth, Calc and SEPAL. Open Foris tools are being built to support the entire inventory lifecycle: needs assessment, design, planning, field data collection and management, estimation analysis, and dissemination. Open Foris can also be used for collecting and managing any other kind of data, such as socio-economical or biodiversity data.

planned for. As such, the following should be considered in choosing software packages:

- Suitability for the tasks
- Total operational cost including hardware and other requirements
- Ease of use and access (e.g. via the web or internal systems only)
- Access to experts, training and support (a strong user community helps)
- Ability to move to other platforms in the future (data formats, etc.)
- Reliability (e.g. up-time, stability)
- Need and cost of modifications
- Automation and links to other systems
- Licensing restrictions

Equipment for fieldwork

Collection of ground data (e.g. associated with **National Forest Inventory**, **intensive monitoring sites**, and **other ground data sources**) requires an array of equipment ranging from small and simple measuring equipment, such as compasses and tape measures, to more sophisticated technology such as global positioning system and electronic data collection devices,(18) to large assets such as appropriate vehicles (4WD and boats) to facilitate site access. There are many manuals available detailing suggested field equipment lists (FAO, 2008; Walker *et al.*, 2012; and Huy *et al.*, 2013), which those who are responsible for conducting field measurements can use in infrastructure planning. As with hardware and software, appropriate storage facilities are required and there are initial capital expenditure costs and ongoing operational costs to maintain the equipment.

Laboratories and analytical equipment

Some samples collected from the field may require analytical processing in scientific laboratories to generate the required data inputs to the NFMS. Such laboratories can be expensive to establish and are usually beyond the operational mandate of the government institutions. In such cases, **strengthening relationships with research and development** or the establishment of **external partnerships** may be the most cost effective and appropriate method of processing field samples.

The previous discussion on hardware and software issues is relevant to the establishment of laboratories for processing of remotely sensed data. It is also worth noting that the large variety of readily available **remotely sensed data sources** give countries access to an unprecedented wealth of information. With this also comes challenges in terms of computing power and storage limitations, which may be overcome with new developments in geospatial data infrastructure (**Box 8**) that can support the operation of local laboratories.

Financial Considerations

When considering infrastructure, numerous financial issues need to be addressed, such as separation of capital and operational expenditure, separation of funding sources (e.g. donor vs government),

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(18) The reduction in the cost of handheld computers (e.g. cellphones) has facilitated the access of countries to field data collectors. Experience shows that the use of field data collectors with data collection software, which include validation rules and **QA/QC procedures**, enhances the quality of the data collected by correcting obvious errors and enabling more automation in the quality control. Plus, the data become available more quickly and are readily backed up.

depreciation, sales of used equipment and general procurement rules. Employing the services of a quality accountant and budget manager early in the system design process can greatly increase the chances of creating a long-term operational program by providing a clear long-term cost profile.

Consideration of both capital and operational cost of an NFMS during the **technical design decision** stage can influence the financial sustainability of the system. Capital costs are typically large one-off outlays, the scale of which will be dependent on the methodological approach adopted and the amount of infrastructure and data already available. Operational costs are on-going or recurring to generate repeated REDD+ emission and removal estimates. A long-term view of costs will help to avoid design decisions that may be cheaper, or financially supported by external partners, in the short-term, but which are more costly or unsustainable in the long-term.

Regular **evaluation of the required NFMS infrastructure** and associated capital and operational budgets is recommended.

Box 8: Cloud infrastructure in support of processing large data sets

Cloud computing is the on-demand availability of computer system resources, especially data storage and computing power, without direct active management by the user. The term is generally used to describe data centres available to many users over the internet. In the context of an NFMS, two viable options for countries are to assess cloud commuting services and cloud geospatial data infrastructure.

- **Cloud computing -** cloud computing involves delivering different types of service over the internet, from software and analytics to secure and safe data storage and networking resources. This enables countries to have access to large performance services that would not otherwise be available and to take advantage of economies of scale, recognising that unreliable or limited internet connection may represent a challenge to adoption. Consideration of the use of cloud computing for certain processes is consistent with national data policies and security requirements. Several countries currently rely on cloud computing for part of their processes.
- **Cloud Geospatial data infrastructure -** the affordability of cloud computing services and open-access to satellite imagery is enabling the creation of new geospatial data infrastructure. A range of different initiatives have created the necessary infrastructure to enable processing satellite imagery in the cloud and range in cost to access. Countries are increasingly moving some steps of their processing chains onto these platforms, combining in many cases, cloud processes with local processes. For example, countries use these platforms to create cloud-free composites that they then process locally, thus reducing the amount of imagery to download.

Some examples of tools include:

SEPAL

The System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) is a collaboration between FAO and Norway. SEPAL is a cloud-based computing platform for geospatial big data processing and storage. It offers direct access to satellite data sources through a graphical user interface, including fine resolution data (e.g. Planet data), a set of open-source software tools and modules, and the capacity to run customised Python scripts and data processing chains on a virtual machine hosted by Amazon Web Services. SEPAL is free of charge but provides a limited number of virtual coins that can be used for processing.

Google Earth Engine

The Google Earth Engine is a cloud-based platform for planetary-scale environmental data analysis. It combines a petabyte-scale archive of publicly available remotely sensed imagery and other data with Google's computational infrastructure optimised for parallel processing of geospatial data. This includes APIs for JavaScript and Python, and a web-based IDE for rapid prototyping and visualisation of complex spatial analyses and the Landsat and Sentinel data sets. However, it is only available free of charge for research, education and non-profit use, and accessing and processing data is not open-source. Countries should consider their data policies when running certain processes in this platform.

Forestry TEP

Forestry Thematic Exploitation Platform (F-TEP) is an EO data processing and analysis platform under development by ESA. The aim is to create a *one-stop-shop* of forestry remote sensing services for academic and commercial sectors. The service will offer large pre-processed satellite data archives, in addition to computing power and easy-to-use data processing tools and GIS software. The objective is to encourage the use of data from the Sentinel satellites to support forest ecosystem monitoring and sustainable forest management. The project is in a pilot phase, focusing on forest management in Finland and Mexico, and is not open to general use. It currently incorporates some tools relevant for developing countries, such as the Satellite Monitoring for Forest Management tools **https://www.smfm-project.com/** for monitoring of dry forests.

The European Commission Copernicus Data and Information Access Services (DIAS) platform

The European Commission's Copernicus Data and Information Access Services (DIAS) is composed of five cloud-based platforms providing centralised access to Copernicus data and information, as well as to processing tools. These online platforms allow users to discover, manipulate, process and download Copernicus data and information and provides access to Copernicus Sentinel data, as well as to the information products from Copernicus' six operational services, together with cloud-based tools (open-source and/or on a pay-per-use basis).

Amazon Web Services

This platform has a dedicated section for EO data sets and is available on a pay-per-use basis. Aside from the commercial nature of the platform, countries should be aware that not all the historical Landsat archive is available on this platform and that tools are not implemented, thus requiring countries to have programming capabilities to implement their processes in the cloud.

Sentinel Hub

Sentinel Hub is an engine for processing of petabytes of satellite data, including Sentinel, Landsat and other Earth observation imagery. It relies partly on Amazon Web Services, and makes the imagery accessible for browsing, visualisation and analysis. The system can be scaled globally with an intuitive and user-friendly interface. It has several free options, and its full functionality can be exploited for a fee. The program is partially-funded by the European Union and others.

1.3.4 Documentation

Documentation of design decisions, assumptions, data, methods and operational elements help internal and external communication of the system and maintain institutional memory.

For effective sustainable operation and communication of a National Forest Monitoring System, it is critical that all aspects of the system is documented in detail and accessible to relevant stakeholders (**Section 1.3.2**).

The types of system documentation include:

- **Requirements -** Documentation of the system requirements including attributes, capabilities, characteristics, or qualities. This is the foundation for what will be or has been implemented.
- **Architecture/Design -** Overview of the system that includes relationships to other systems where relevant and principles to be used in design of components. Design documents describe the institutional arrangements, roles and responsibilities, all technical and administrative processes, system documentation and internal and external reports generated by the system.
- **Technical -** Documentation of the methods, approaches and tiers adopted and explanation of all national data sources, how they are applied, assumptions, limitations. It also provides the overarching design decisions such as forest definition, stratification, land use/land cover classification systems, carbon pools, gases etc.(19)
- **Operational -** Manuals and standard operating procedures (SOPs) are primarily for the technical users of the system, system administrators and support staff. These documents represent simple clear instructions to ensure that all routine operational processes are conducted in a consistent manner and in accordance with defined quality standards. Usually, SOPs should set out the objectives/purpose, resources needed, roles and responsibilities, procedure/instruction for the operation, QA/QC procedures and recording/archiving procedures. It is important that the SOPs are detailed enough to enable replication of the operations, and that this is updated regularly when consistency issues are identified in implementation of the process, e.g. inconsistencies in measurements due to insufficient descriptive guidance.(20) For complex processes, these SOPs may be provided with a manual that offers more detail in the application of the SOPs, e.g. an inventory manual, or a land cover interpretation manual.(21) SOPs should be developed for each process of the system and made available to the responsible people identified in the Design Document.
- **Communications -** Communication of the NFMS can be both internal and external. Development of a communications plan to meet the diverse range of stakeholders generally involved with the NFMS is recommended. A range of diverse communication formats including documents, online portals and websites, presentations and imagery can help to strengthen internal institutionalisation and build capacity. Targeted material for external communications such as sharing of experiences and participating in verification processes is also very valuable.

For all documentation it is important to have a version control system in place so as to enable update in response to process improvements and avoid multiple versions being used (e.g. data collection and analysis should be stored in a way that the metadata makes reference to a specific version of the

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(19) Useful templates for documenting the NFMS framework are available from the USEPA's **Developing a national greenhouse gas inventory template workbook**.

(20) An example of SOPs may be found in Vallejo *et al.* (2011).

(21) An example of interpretation protocol may be found in **BNCR, 2018** or **GIMBUT, 2018**.

relevant documentation).

1.3.5 Quality assurance and quality control

A QA/QC system contributes to the objectives of good practice in inventory development, namely to improve the transparency, consistency, comparability, completeness, and accuracy of national greenhouse gas inventories. QA/QC is a system-wide principle and should be embedded in all processes of the NFMS where data are collected, stored, generated and reported.

QA and QC are defined by the IPCC(22) as follows:

- **Quality assurance (QA) -** a planned system of review procedures conducted by personnel not involved in the inventory development process (e.g. review of a subsample of sample data by a team not involved in the data collection).
- **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 (e.g. regular training for data collection), quick review of the data collected, use of rules to avoid inconsistencies in data collection.

A written QA/QC plan is fundamental to a QA/QC system. **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** (23) A QA/QC plan outlines QA/QC activities performed, the personnel responsible for these activities, and the schedule for completing them. Coordination mechanisms, a risk assessment and review procedures required to implement the plan can be summarised as:

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 that meet established **record keeping** processes; and
    - Coordinates external reviews of estimates and reports and ensures that comments are incorporated.
2. **Risk assessment -** A risk assessment is an important piece of a robust QA/QC plan. For instance, data collection activities usually present substantial risks for error, misstatements or omissions, so there is a need to concentrate system controls to ensure that this risk is mitigated. This risk assessment enables the concentration of scarce resources for QA/QC procedures where there is a more significant risk of errors.

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(22) IPCC Good Practice documentation provide valuable reference material for QA/QC. Both **Section 5.5 of the GPG2003** and **Volume 1, Chapter 6 of 2006GL** provide useful general guidance. **Volume 4, Chapter 4 of 2006GL** provides additional material on QA/QC issues relating to the lands sector.

(23) And in EPA's **Developing a national greenhouse gas inventory template workbook**.

3. **Review procedures -** Although general QC procedures are designed to be implemented for all categories and on a routine basis,(24) 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:(25)

- 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; and
- the review approach and findings are documented and considered in continuous improvement processes.

Box 9 suggests a checklist for internal review 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 collected;
- any limitations in the approaches identified;
- comparisons that have been performed with independent inventories, data sets, 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;
- 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 prioritisation; and
- identification of capacity building needs where relevant.

The outcomes of QA/QC processes may result in a reassessment of inventory or category estimates or uncertainties, and in subsequent improvements to the estimates of emissions or removals. For example, the results of the QA/QC process may point to particular variables within the estimation methodology

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(24) **GPG2003, Section 5.5** or **2006GL, Volume 1, Section 6**.

(25) Adapted from **GPG2003 Section 5.7.3**.

for a certain category that should be the focus of improvement efforts.

Box 9: Suggested internal review checklist for REDD+

Suggested internal review checklist for REDD+:

- 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 Land Use, Land-Use Change and Forestry (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 subsets 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:

- Crosscheck 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).

Use of quality tools:

- Different quality tools may be used to identify quality issues: Control charts, Ishikawa diagrams, Flowcharts, Check sheets, Pareto diagrams, scatter charts.

Many data checks can be automated 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**.

1.3.6 Continuous improvement

The development of an NFMS and associated MRV function should include a continuous improvement process that is recognised as a good practice by the IPCC Guidelines and Guidance and is promoted through the use of **key category analysis**, uncertainty analysis,(26) **QA/QC** and verification activities.(27) Under the Warsaw Framework on REDD+, countries may also develop their FREL/RRLs following a step-wise approach to periodically incorporate better or new data, additional pools and improved methodologies(28) recognising the need for continuous improvement.

Continuous improvement processes may build on existing tools that are used to improve, optimise and stabilise business processes and designs based on a multi-step iterative process such as the Plan-Do-Check-Act (PDCA)(29) and the Define-Measure-Analyse-Improve-Control (DMAIC).(30)

A continuous improvement process should be conducted regularly and can be most effective when aligned with reporting events, budget cycles or important deliverables. These particular events can trigger QA/QC responses and result in verification findings that can be used in the evaluation phase of the Plan step. The evaluation phase can include conducting a thorough review of NFMS elements combined with a series of interviews / workshops with the NFMS implementation team and relevant stakeholders (**Section 1.4**).

The findings from this evaluation phase can then be combined with an understanding of key categories affecting the estimates from the NFMS. It is unlikely that all identified improvements in the evaluation phase will be able to be completed in the continuous improvement cycle due to a range of reasons including budget, capacity, technology, and time constraints. **Key category analysis** can be helpful in prioritising the improvements that will have the largest impact on improving the estimates.

Embedding a continuous improvement process in the NFMS operational framework can improve capacity and understanding of roles and responsibilities and ultimately lead to more accurate and transparent NFMS outputs all characteristics of a **mature operational system** that can deliver consistent outputs which meet national reporting objectives.

1.4 Maturing of NFMS through system representation and analysis

An NFMS and its MRV functions are typically built on existing systems where possible (e.g. existing mandates, data and/or reporting processes). Although it is recommended to establish **Foundation**, **Strategic** and **Operational** elements for an effective NFMS, in general, NFMSs have grown

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(26) The IPCC outlines the role of uncertainties in continuous improvement in **Volume 1, Chapter 3, of the 2019 Refinement** (IPCC, 2019).

(27) A number of concepts and tools in the **2006 IPCC Guidelines, Volume 1, Chapter 6** are provided to support efficient inventory management, checking and continuous improvement. These activities will ensure that the best use of limited resources can be made and a quality consistent with good practice is achieved for each inventory.

(28) **UNFCCC decision 12/CP.17, para 10**.

(29) **Plan:** Evaluate the system, identify opportunities and plan for change. **Do:** Implement the change on a small scale. **Check:** Use data to analyse the results of the change and determine whether it made a difference. **Act:** If the change was successful, implement it on a wider scale and continuously assess your results. If the change did not work, begin the cycle again.

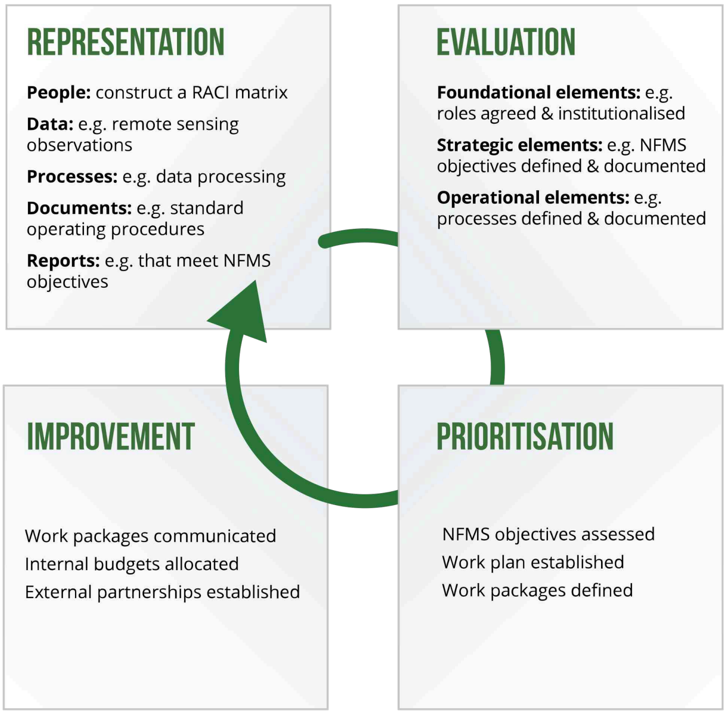
(30) **Define** the problem, improvement activity, opportunity for improvement, the project goals, and customer (internal and external) requirements. **Measure** process performance. **Analyse** the process to determine root causes of variation and poor performance (defects). **Improve** process performance by addressing and eliminating the root causes. **Control** the improved process and future process performance.

organically, sometimes with more focus on particular areas of interest or strengths of those involved. It is not uncommon that those operating within the system do not comprehend the full system structure nor any impact that they may have through certain decisions made to address their particular part.

When considering system improvements, it is recommended to conduct a repeated process of system representation, evaluation, priority setting and implementation of improvements in the context of the full scope of the entire NFMS. Systems thinking is a holistic approach to analysis that focuses on the way a system's constituent parts interrelate. System analysis (**Figure 2**) requires:

- **Representation -** understanding what exists and representing how the parts interact;
- **Evaluation -** assessment of how the system parts are performing;
- **Prioritisation -** identification and prioritisation of system improvements; and
- **Improvement -** communication and implementation of identified priority improvements.

Figure 2: Maturing of an NFMS through the repeated process of system representation, evaluation, priority setting and implementation of improvements



Outputs from this exercise can assist communication with internal and external partners and alignment of objectives, making effective use of resources and reducing duplication of effort in addressing the identified needs.

1.4.1 System representation

The process of system representation assists in understanding what exists and representing how the system parts interact. The system representation process facilitates the structured identification of existing resources and gaps to identify requirements to progress towards implementation of an operational, mature and effective NFMS.

Any approach to system representation should avoid a silo mentality(31) wherever possible. The approach should be an open, multi-agency, participative, constructive and collaborative exploration of the system that:

- identifies needs within the existing country's context and national goals;
- focuses on assessing and improving the tangible elements of a country's NFMS (i.e. data, processes, documents and reports); and
- identifies work packages that progress and mature the operation of their NFMS.

While silo thinking should be avoided, it may be helpful to consider stages within the system to initiate the system mapping exercise (e.g. data, data processing, integration, reporting, and system-wide issues), noting that there are generally no firm boundaries between these stages. The systems parts within these stages could be represented as:

- **People -** people are an important element of a system and can be either Internal or External to the system or its sub-system parts.
- **Data -** represent both inputs to and outputs from the system.
- **Processes -** processes are conducted by people to drive the system and rely on inputs such as Data, Documents, Reports to produce a number of outputs including Data, Documents, Reports.
- **Documents -** documents support instruction, transparency and assist in consistent system outputs through time.
- **Reports -** reports represent outputs of the system and are indicators of the system meeting MRV objectives.

Typically, for each system task there will be a people, process and document part. In some cases, this also may include a data part, either as an input or output, and may also include a report. For example, the system requires collation of remotely sensed images (i.e. data) every year. This task is the responsibility of the GIS unit in the Ministry of Forestry (i.e. people). The process that it has established ensures that all available national data are collated from Landsat archives by the end of December each calendar year, ready for processing (i.e. process), and that the GIS unit has documented the process in a standard operating procedure (i.e. document).

1.4.2 System evaluation

Once the current system has been mapped, system evaluation can help to identify what is working well and what may require improvement. Goal-based, goal-free and criteria-based approaches are three different attitudes to apply in evaluating system performance (**Box 10**).

A typical evaluation framework of the system parts (e.g. data, processes, documentation and reports) may be:

- **Present -** There is evidence that the system part is clearly visible within the NFMS. While it is present, it may not be suitable, operational or effective. For example, standard operating

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(31) A silo mentality is a reluctance to share information with employees of different divisions in the same company. This attitude is seen as reducing efficiency and, at worst, contributing to an ineffective system.

procedure templates may be available for all NFMS tasks, but they are incomplete for some tasks.

- **Suitable -** Implementation in the NFMS is suitable based on NFMS objectives and complexity. For example, the SOP for generating activity data on an annual basis has been written by the national team responsible for generating the activity data, but no training has been provided in how to follow the procedures outlined in this SOP to make it an operational part of the annual NFMS work plan of the unit responsible.
- **Operational -** There is evidence that the system part is in use and an output is being produced. For example, the SOP is being used for instructing responsible staff to produce time series consistent activity data as an input to the integration framework of the NFMS.
- **Effective -** There is evidence that the system part is effective in achieving the desired outcome for the NFMS. For example, the SOP is being used for instructing responsible staff to produce time series consistent activity data as an input to the integration framework of the NFMS, which is capable of producing output reports that meet the objectives of the NFMS.(32)

A system can functionally meet its objectives with system parts that are present and suitable and other parts that are operational and effective. For example, activity data (i.e. the data part) may be considered operational; however, the documentation related to their generation (i.e. the document part) may only be considered present (e.g. there is a template but the people responsible for the generation of the activity data have not completed the documentation to enable instruction of others, increasing the risk of inconsistencies within this repeated process). Nonetheless, reports can be produced that meet the NFMS objectives. However, if the documentation was available, the NFMS would operate more effectively and with less risk.

It is recommended that people are not considered in this PSOE form of evaluation, but rather that a RACI matrix (**Box 11**) is developed to communicate and co-ordinate the people within the system. A RACI matrix is a responsibility assignment chart that maps out every task, milestone or key decision related to the NFMS and assigns which roles are Responsible for each action item, which personnel are Accountable, and, where appropriate, who needs to be Consulted or Informed. Establishing such a consensus by employing the RACI matrix almost always gets stalled actions in the NFMS moving again, and enables the key stakeholders to readily deal with the other issues that require resolution.

The four stakeholder roles considered in a RACI matrix are those:

- **Responsible -** People or stakeholders who do the work. They must complete the task or objective or make the decision. Several people can be jointly responsible.
- **Accountable -** Person or stakeholder who is the owner of the work. He or she must sign off or approve when the task, objective or decision is complete. This person must make sure that responsibilities are assigned in the matrix for all related activities. Success requires that only one person should be accountable for each task.
- **Consulted -** People or stakeholders who need to formally give input before the work can be done and signed-off on. These people are active participants.
- **Informed -** People or stakeholders who need to be kept updated, but are not actively involved. They need updates on progress or decisions, but they do not need to be formally consulted, nor do they contribute directly to the task or decision. There may be some actions where no people

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(32) The PSOE evaluation framework is commonly applied in systems analysis, most widely in the aviation and safety management sectors.

or stakeholders are informed.

Assignment of appropriate responsibilities and clear communication of these can avoid a number of operational issues. The most effective NFMS will have assigned the most skilled and cost effective human resources to roles of operational responsibility. These can be both internal institutions and external stakeholders and partners. Roles of operational accountability are typically held by those with policy and budgetary responsibility and are typically internal institutions.

Box 10: System Evaluation Approaches

Goal-based, goal-free and criteria-based approaches are three different attitudes to apply in evaluating system performance.

Goal-based evaluation

Goal-based evaluation is one of the most traditional and straightforward approaches to assessing the extent to which a system has delivered on its stated goals or objectives. The FAO **Forest Monitoring Scorecard** is an example of this evaluation technique and is used as a basis for rating country capacity in forest monitoring. The 28 indicators fall into four sets, which reflect the three NFMS pillars as defined by FAO (i.e. satellite land monitoring systems, national forest inventories, emissions estimates). The basic strategy of this approach is to measure if predefined goals are fulfilled or not; to what extent and in what ways. What is measured depends on the character of the goals. A limitation of this approach is that it may not identify unintended outcomes, which can be as important as the stated goals. Goal-based evaluation tends to concentrate on technical and economic aspects rather than human and social aspects of a system, which can lead to negative consequences in terms of decreased user satisfaction, but also broader organisational consequences in terms of system value and acceptance.

Goal-free evaluation

Goal-free evaluation is a more interpretative approach, which aims to gain a deeper understanding of the nature of what is to be evaluated and to generate motivation and commitment. The involvement of a wide range of stakeholder groups is often considered essential to this approach to evaluation. This can also be a practical obstacle, where time or resources for the evaluation are short. Goal-free evaluation is defined as gathering data on a broad array of actual effects and evaluating the importance of these in meeting demonstrated needs. The evaluator makes a deliberate attempt to avoid all rhetoric related to goals; only the outcomes and measurable effects are studied. The aim of goal-free evaluation is to:

- avoid the risk of narrowly studying stated objectives and thereby missing important unanticipated outcomes;
- remove the negative connotations attached to the discovery of unanticipated effect (e.g. use of terms such as side effect or secondary effect often used in goal-based evaluation to describe unintended outcomes to defined goals);
- eliminate the perceptual biases introduced into an evaluation by knowledge of goals; and
- maintain evaluator objectivity and independence through goal-free conditions.

The basic strategy of this approach is inductive evaluation. The approach aims to discover qualities of the object of study. The evaluator makes an inventory of possible problems, and the knowledge of the system emerges during the progress of the evaluation.

Criteria-based evaluation

Criteria-based evaluation relies on checklists, heuristics, principles or quality ideals where the interaction between users and the system acts as a basis for the evaluation, together with a set of predefined criteria. The basis for these action-oriented ideals is to understand if and how the system supports the actions required. Setting evaluation criteria provides focus on certain qualities that, according to the perspective of the assessor, are important to evaluate. Attention to set criteria can also de-emphasise other qualities. As such the criteria chosen governs the evaluators attention and thereby the kind of knowledge the evaluator achieves.

Box 11: RACI Matrix Considerations

How to create a RACI matrix

A simple process for creating a RACI matrix includes the following six steps:

1. Identify all the tasks involved and list them on the left-hand side of the chart. A simplified example for parts of an NFMS is illustrated below.
2. Identify all the project stakeholders and list them along the top of the chart.
3. Complete the cells of the model identifying who has responsibility and accountability, and who will be consulted and informed for each task.
4. Ensure that every task has at least one stakeholder *Responsible* for it.
5. No tasks should have more than one stakeholder *Accountable*. Resolve any conflicts where there is more than one for a particular task.
6. Share, discuss and agree on the RACI model with your stakeholders. This includes resolving any conflicts or ambiguities.

Table 1: Illustration of a simplified RACI

Step/ Action	REDD+ Unit	Forest Mapping Unit	Information Management Unit	Ministry of Forestry	Steering Committee	Consultant	External Partner
Collect data	C	R	C	A	I		
Catalogue data	C	C	R	A	I		
Process data	C	R	C	A	I		
Conduct QA/QC process	C	C	I	A	I	R	
Release report	R	I	I	A	C		I

RACI matrix best practices

Simply creating a RACI matrix is not enough. It is important to ensure that the matrix maps to a successful strategy and that any conflicts and ambiguities are resolved. This involves looking across each row and up and down each column of the matrix for the following:

- **No A's -** Who is *Accountable* ? There must be one *A* for every defined step. One stakeholder must be *Accountable* for the thing happening. Accountability is typically held by those with policy and budgetary responsibility, typically internal institutions.
- **More than one A -** Is there confusion on decision rights? Those with accountability have the final say on how the work should be done and how conflicts are resolved. Multiple A's can invite slow and contentious decision-making, but may be necessary where technical and budgetary accountability are separated.
- **No R's -** Who is doing the work in this step and getting things done? This can be internal human resources or external consultants.
- **Are there too many R's? -** Does one stakeholder have too much assigned to them? Does the stakeholder need to be involved in so many of the activities? Can *Responsible* be

changed to *Consulted*, or *Informed* ?

- **Every box filled in -** Do all the stakeholders really need to be involved? Are there justifiable benefits in involving all the stakeholders, or is this just covering all the bases and potentially unnecessarily slowing the decision-making process?
- **A lot of C's -** Do all the stakeholders need to be routinely *Consulted*, or can they be kept *Informed* and raise exceptional circumstances if they feel they need to be *Consulted* ? Too many Cs in the loop can slow progress down.
- **Are all true stakeholders included in this model? -** Sometimes this is more of a challenge to ensure, as it is an error of omission. This is often best addressed by a steering committee or management team.
- **Buy-in -** Does each stakeholder totally agree with the role that they are specified to play? When such agreement is achieved, it should be included in the NFMS documentation.

1.4.3 Prioritisation

Following the completion of system representation and evaluation a number of gaps or possible improvements will be identified. Priorities need to be set to implement improvements within time and budget constraints. A goal-based analysis using a combination of the PSOE evaluation framework with a checklist(33) can help to group and prioritise improvements. Generally, the checklist will be a restricted view because it has been developed with a specific objective in mind. When setting priorities and budgets, consider the checklist across the system and assess all the implications of the change, on people, data, processes, documents and reports. It may also be appropriate to incorporate any outputs from a **key category analysis** in the prioritisation process.

1.4.4 System improvement

The process of system representation and evaluation should have enabled the identified and prioritised improvements to be represented at a level to enable a Work Package(34) to be developed. A Work Package is like a mini-project within the NFMS and is an easier element to understand for the project team responsible. Team members are able to see the connection between different task strands across the NFMS, while still being able focus on those that apply to them. The completion of a work package can be a dependency for other work packages. Using work packages to manage system improvements provides a greater level of clarity, as each block of connected tasks can be easily visualised.

A Work Package is a detailed description of requirements to complete a specified task. This includes elements such as a budget, material(s), human resources, and schedules and milestones. The scope of each package is generally defined by the fact that they have the following characteristics in common:

- Nature of work involved
- Outcomes of the tasks
- Geographical location where tasks take place
- Time when tasks will be completed
- Technology or materials that will be used
- Team leaders in charge
- Specific stakeholders

Human or financial resources will be needed to complete the tasks outlined in the identified priority Work Packages. In this context, effective **institutional arrangements** will help to progress priority improvements to the system.

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(33) Checklists can be, for example, a set of system-wide actions, programme-specific checklists, or internal/external review findings. REDDcompass uses a range of Actions categorised as Minimum, Refined and Advanced to represent system maturity. There are also tailored checklists available on **REDDcompass** from a range of GFOI partners, which may also be of relevance depending of the objective of the evaluation.

(34) An annotated Work Package template is available from the GFOI Country Needs Assessment Workshop Materials.

Chapter 2 Technical Design Decisions

This chapter describes methodological-related and policy-related design decisions relevant to the establishment of an operational NFMS, noting that NFMS functions will vary based on national specific monitoring and reporting objectives and circumstances.

2.1 Monitoring goals and scope under the UNFCCC

A sustainable operational NFMS collects, processes and integrates data to produce information on the status, as well as the trend through time, of the many forest variables of interest that meet national reporting objectives responding to pre-defined goals.

The MGD focuses on goals associated with the reporting requirements under the UNFCCC, which refer to the sink and reservoir functions of forests, although elements and instruments might be used to monitor other variables of National interest, such as biodiversity, sustainable forest management or desertification.

Decisions to the UNFCCC and its Paris Agreement outline specific reporting requirements. The Convention (UNFCCC, 1992)(35) Articles 3 and 4 and its Paris Agreement (UNFCCC, 2015)(36) Article 5 recognise both the relevant role of terrestrial carbon sinks and reservoirs in the atmospheric concentration of CO_2 and ultimately on the global warming and associated climate changes. Accordingly, Article 4 of the Convention and Article 5 of the Paris Agreement require countries to take actions and to report on those actions, including on progresses towards Article 12 of the Convention and Article 13 of the Paris Agreement. Accordingly, all countries have to regularly submit information to the UNFCCC on the policies and measures taken to address climate change and time series of estimates of all anthropogenic emissions and removals, to determine the net flux, as well as its trend across time. To do so, the UNFCCC established reporting requirements that were different for Annex I and Non Annex I Parties to the UNFCCC, in terms of content and frequency of information reported. As a general rule, Annex I countries needed to report more often and in greater detail. Under the Paris Agreement, reporting requirements are equal across all countries, although flexibility is allowed to Non Annex I countries that need it. **Figure 21** shows the reporting requirements for Annex I and Non Annex I countries prior to and under the Paris Agreement Transparency Framework.

In summary, the first reporting instrument under the UNFCCC was the National Communication, which Annex I shall and Non Annex I countries should report upon request. The reporting cycle is currently of 4-years, with flexibility for Non Annex I countries, in particular for least developed countries (LDCs). The National Communication does include the national GHG inventory of all anthropogenic emissions and removals occurring on the country's territory, as well as information on mitigation, and adaptation, actions taken or planned to be taken by the country.

Since 2014, the timing of submission of information has been established as biennial for all countries, with flexibility for Non Annex I countries, in particular for least developed countries: Annex I countries have had to submit Biennial Reports (BRs) on progress since their last National Communication, while Non Annex I countries submit Biennial Update Reports (BURs) to update information contained in their last National Communication. Both the Biennial Reports include the GHGI. The REDD+ FREL/FRL is reported as a stand-alone document at the discretion of the country.

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(35) **https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf**.

(36) **http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf**.

If a FREL/FRL is voluntarily submitted, the BUR is also the reporting instrument where MRV information on REDD+ results and information on the NFMS is reported.

BRs and BURs are replaced under the Paris Agreement by the Biennial Transparency Report (BTR), thus setting a unique standard for all Parties of the Agreement; however differences remain in the reporting for support (mandatory only for Annex I countries) and flexibility on some elements is allowed for Non Annex I countries that need it (e.g. LDCs and Small Island Developing States (SIDS) can submit BTRs whenever they can).

The BTR contains information on national GHG emissions and removals as well as on actions taken and associated progress to achieve the NDC, including those taken under REDD+. Further, every five years, countries must also submit their Nationally Determined Contribution, which very likely includes forest land and might include REDD+ activities.

All these reports need to be fed with information on GHG estimates, as well as on mitigation and adaptation activities. Given that the sustainability of the reporting framework is a paramount principle, a single monitoring system to collect all forest-related information needed for the multiple reports should be developed. Such a system needs to be robust, have national coverage, sustainability across time and national ownership.

GHG emissions and removals are estimated in forest land from the carbon stock gains and losses. Those, and the associated underlying drivers, occur in forest land at a different pace through time. Gains are almost continuous while losses are mostly immediate. Accordingly, activities aimed at reducing carbon stock losses benefit from real-time information on when and where those carbon stock losses actually occur in order to plan and implement suitable mitigation procedures (e.g. fire) suppression, halting illegal logging).

Thus, within a time schedule suitable to meet the reporting cycle (i.e. biennial(37) and quinquennial,(38)) the NFMS is required to:

1. Regularly collect primary information and collect/compile auxiliary information
    - Primary and auxiliary information to estimate GHG emissions and removals from managed forest land across the national territory.
    - Auxiliary information for verification of GHG estimates.
    - Auxiliary information on activities to which GHG emissions and removals are associated, to be used for business as usual scenario projections as reference point, level, baseline, and/or for adjustments of the REDD+ reference level, if any.
    - Auxiliary information on the implementation of mitigation, and adaptation, activities related to forest land (e.g. forest) sustainable management plans), information on REDD+ safeguards, support received and support required.
2. Collect information continuously on drivers of carbon stock losses, and other impacts to be mitigated, to allow measures to mitigate such losses/impacts to be taken in a timely manner.

The scope of the NFMS, as per the UNFCCC reporting needs, requires the collection and compilation of time series information across the entire country's territory: it should be continuous to detect any

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(37) GHG estimates are annual (i.e. the sum of all anthropogenic emissions and removals that occurred within a year).

(38) For Nationally Determined Contributions and Forest Reference Levels.

disturbances(39) causing tree cover loss, to allow for mitigation measures to be implemented in a timely manner and to allow for the regular reporting of all information needed to the UNFCCC.

Decision 11/CP.19 provides for methodological requirements of information collected and compiled by the NFMS. Information needs to be compliant with the most recent IPCC guidelines and guidance adopted or encouraged by the COP, which under the Paris Agreement means the 2006 IPCC Guidelines together with the Wetlands Supplement, and be transparent and consistent over time and suitable for MRV of REDD+ activities. This implies that the NFMS collects all information needed (i.e. complete) with an accuracy and precision suitable for preparing good practice estimates of GHG emissions and removals associated with land under REDD+ activities. The 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. It should reflect, as appropriate, a phased approach,(40) this means that it is expected to be built step-by-step under a learning-by-doing approach. Furthermore, this decision acknowledges that the NFMS may provide, as appropriate, relevant information on how the safeguards set out in **Appendix 1 to decision 1/CP.16** are addressed and respected.

When the NFMS is built following a step-wise approach, the so-called displacement of emissions (also referred to as leakage), is to be addressed. Displacement represents any impact from increasing emissions or reducing removals that occur outside the area monitored. Adopting National scale monitoring deals with displacement because the whole country is covered (i.e. no forest land area is left outside REDD+ boundaries), as well as helpful is the integration of REDD+ activities within the land sector reporting under the Paris Agreement NDC (i.e. no land area left outside accounting). This means that, where subnational or project scale monitoring is occurring, the risk of missing emissions due to displacement is high, while monitoring at national level, while engaging actors at local, state or department levels to ensure the **subnational monitoring of project activities** as an interim step would address the displacement of emissions during the interim phase of moving from subnational to national monitoring, reporting and verification. Nesting REDD+ projects is a way to deal with subnational implementation while ensuring consistency at national level and possibly achieving coverage of the entire national territory (**Box 23**).

Nevertheless, in the case of subnational coverage (e.g. at state, province or project level), displacement at the national level of emissions needs to be monitored and reporting on how displacement of emissions is being addressed required.(41)

When establishing subnational systems, it is important to consider how the system will eventually be included consistently within the final national system and which components can be used at national level for subnational estimates.

Emissions and removals from REDD+ activities are quantified in the context of the national GHGI, reported through the BUR (**Chapter 6**) and performance measured against national FREL/FRLs.

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(39) Here this has a broad meaning to indicate any loss not associated with natural turnover. It therefore includes all human activities and disturbances, as well as all natural disturbances.

(40) See **paragraphs 73 and 74 of decision 1/CP.16**, where it is established that a phased approach begins with the development of national strategies or action plans, policies, 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.

(41) See **decision 1/CP.16, paragraph 71, footnote 7**.

2.2 Reporting harmonisation

For reasons of transparency and consistency,(42) and for a range of other efficiency reasons, countries are expected to use, where possible, the same approaches, methods and data for reporting forestry emissions in national GHGI and REDD+ reports. This recommendation of consistency across reports is also valid for non-GHG reports on forests for which the NFMS provides data.(43) However, there are reasons for which REDD+ and GHGI estimates are not yet be fully aligned (i.e. GHGI estimates contain national estimates of emissions and removals from land use and land-use change, while REDD+ estimates are for activities which may be subnational as an intermediate step, where better data were collected but not available at national level). It is important to document any differences and to understand and communicate the underlying causes and implications.

Some possible areas where harmonisation should be considered include:

- roles and responsibilities within and between stakeholders
- land use definitions
- attribution rules
- data sets, including both collection and processing protocols(44)
- assumptions made
- approaches, methods and tiers adopted
- treatment of key categories

2.3 Use of IPCC good practice guidance in the context of the UNFCCC

Since 1995, the IPCC has published the methodological guidance that countries have agreed to use in estimating anthropogenic GHG emissions and removals and reporting within the national GHGI to the UNFCCC. **Table 2** summarises the methodological guidance introduced by the IPCC since 1996, covering all sectors, including those related to land use. This section outlines guidance presented in the IPCC Guidelines and Guidance Documents relevant to the land sector and the development of National Forest Monitoring Systems for Measurement, Reporting and Verification in the context of the UNFCCC.

Table 2: 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.

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(42) As requested by COP decisions **12/CP.17**, **11/CP.19** and **13/CP.19**.

(43) Aiming for consistency should not result in avoiding the implementation of a methodological improvement and/or in failing to use more accurate and/or complete data sets. For example, it is not recommended to reduce the quality of REDD+ data in order to be consistent with a dated GHGI.

(44) **Section 4.1** presents advice on data harmonisation.

IPCC Guidance Document	Description
2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006GL)	Consolidates and updates previous guidance. Uses the same methodological framework as the 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 emissions/ removals 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 Land Use, Land-Use Change and Forestry accounting rules agreed for LULUCF for the second commitment period of the Kyoto Protocol.
2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories	The 2019 Refinement updates, supplements and/or elaborates on the 2006 IPCC Guidelines where gaps or out-of-date science have been identified. It is to be used in conjunction with the 2006 IPCC Guidelines and, where indicated, with the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement).

There is a well-established system under the UNFCCC for reviewing inventories of developed countries, and this is the basis for assessing progress towards emissions reduction targets and commitments.(45) In 2011, the UNFCCC decided(46) that the **96GL** in conjunction with the **GPG2000** and **GPG2003** should be used by developing countries for estimating and reporting anthropogenic emissions and removals.(47) 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**. Nevertheless, under the Paris Agreement the reference guidance is the **2006GL**, so the MGD also provides references to corresponding sections of the **2006GL**, its **2013 Wetlands Supplement** and the **2019 Refinement**.

The concept of good practice underpins the **GPG2003** and the **2006GL**. Good practice is defined by the IPCC(48) as applying to inventories that contain “estimates systematically neither over- nor under- the true value 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 maximise 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. Good practice also covers cross-cutting issues relevant to GHGI development, covering data collection including sampling strategies, uncertainty estimation, methodological choice based on identification of **key categories** (i.e. those categories that make the 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, among other things, internal self-consistency checks, and may include checks against independent, or at least independently-compiled data sets and estimates (**Section 1.3.5**).

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).

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(45) UNFCCC 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.

(46) 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 are to use the **2006GL.**

(47) In 2015 the UNFCCC Subsidiary Body for Implementation noted the requests from non-Annex I Parties for training in use of the **2006GLs**, which may also be used for REDD+ (**paragraph 29 of document UNFCCC/SBI/2015/10**).

(48) See **Section 1.3, GPG2003**, or **Section 3 in the Overview in Volume 1 of the 2006GL**.

- Completeness (all relevant categories of emissions and removals are estimated and reported across the entire national territory and across time series).
- Consistency (differences between years reflect differences in emissions or removals and are not artefacts of changes in methodology or data availability).
- Comparability (inventory estimates reported within common formats).
- Accuracy (delivered by the use of methods designed to produce estimates systematically neither under- nor over-the true value and that reduce uncertainties so far as practicable. This addresses both accuracy and precision).

The REDD+ MRV **decision 14/CP.19** refers to these terms except comparability, since there is no agreed format for reporting, and in the REDD+ context completeness is used in the sense that the provision of information shall be enough to allow for reconstruction of the results.

Use of remotely sensed 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 that is necessary for establishing FRELs/FRLs. Generic guidance for maintaining consistency is provided in the GPG2003 and the 2006GL,(49) and a summary specific to issues relating to the NFMS is presented in **Section 2.3.8**. Techniques to maintain time series consistency should also be applied to minimise bias, even if data sources do change over time.

Developing countries may not currently have data and estimates that fully meet these general principles. The most common issues include:(50)

- 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 derived by using IPCC default parameters and factors, 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 accuracy arising from a reliance on expert opinion, independent assessments or model estimations as information sources to produce forest carbon data, in the absence of suitable national specific data.
- Estimates based either on single-date, sample measurements or on integration of 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 Good Practice Guidance 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, these issues still need consideration. The joint use of remotely-sensed and ground-based data as outlined in the MGD can help to address these

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(49) See **Section 5.6 of the GPG2003 (Time Series Consistency and Methodological Change)** or **Volume 1, Chapter 5 of the 2006 GL (Time Series Consistency)**.

(50) **UNFCCC 2009 Technical paper UNFCCC/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.**

issues, in the context of REDD+ activities.

2.3.1 Land categories and conversions

IPCC methods require the identification and tracking of managed land(51) across time and the monitoring of each carbon stock change and associated GHG fluxes. To enhance the accuracy of estimates, managed land is subdivided by the IPCC into six main categories, according to their predominant use (see **Table 3**). The terms land cover and land use may be used interchangeably though they are not synonymous. It is recognised that these categories may incorporate land-cover type, be land-use based, or a combination of the two (e.g. land cover (Forest, Grassland, Wetlands) and land use (Cropland, Settlements)). Land categories significantly differ in terms of resident carbon stocks and their dynamic across time.

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

IPCC Land Category[a]	**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.[b] 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, without human intervention, to exceed 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.

a. The category definitions are from Section 2.2 in the GPG2003.

b. 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.

A further stratification to enhance accuracy is based on the history of the use of land (i.e. tracking the use across time) recognising that any land that is in conversion from one use to another (e.g. a

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(51) Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions.

forest land converted to cropland) has significantly different levels of resident carbon stocks, as well significantly different carbon stock dynamics, compared with that under the same use across time (e.g. a forest land remaining forest land or a cropland remaining cropland). **Table 4** shows land-use categories stratified according to the use across time, and the codes used conventionally for each of those.

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

In general, reporting against the six IPCC land-use categories (**Table 3**) and changes between them (**Table 4**) cannot be achieved on the basis of remotely sensed observations alone. It also requires rules for **attribution** based on spatially-explicit location and auxiliary data (e.g. climate, ecosystem, management type, accessibility) and can be informed by **dense time series analysis**, to establish, for example, whether forest cover loss is due to deforestation (land-use change) or is temporary (no land-use change because tree forest is expected to be replanted or regenerate). In other words, land cover can change temporarily without change in land use, which can inform nationally specific stratification schemes, which are then categorised into the IPCC classes according to national definitions.

The method of determining areas of land use and land-use change should be capable of representing lands according to the definitions applied by the country, and ensure that small losses or additions of forest areas that may lead to the area crossing the forest area definition do not lead to bias in emissions and removal estimates for the activities.

In some cases, the spatial resolution of existing maps or sample units may be coarser than the definitions used to describe some of the land-use categories (e.g. if the Forest Land definition applied by a country includes a minimum area of, say, 1 hectare (ha), but the available land-use data has a minimum mapping unit of 5 ha). This may lead to a situation where:

- small areas of one or more land-use categories are reported under another category; and
- areas of land-use change are either under or overes timated.

Where this occurs, the 2019 Refinement suggests that it is good practice to assess the extent of under- or over-reporting and, where necessary, supplement the results with **further samples** or **auxiliary information** (e.g. concession boundaries, subsidies for land-use changes or land management) that reflect the chosen definitions to validate the results and/or correct for these errors.

2.3.2 Activity based and land based reporting

All greenhouse gas emissions and removals from carbon pools reported in a greenhouse gas inventory produced with IPCC methodologies are based on the identification and tracking of the land, and have the land as the basis to which GHG fluxes are associated.(52) This implies that any CO_2 emissions and

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(52) Land is conventionally assumed to stay in a land converted category for 20-years after the year in which the conversion to a new use occurred. This assumption can be relaxed at higher Tiers, where appropriate

removals that occurred on managed land must be included in the greenhouse gas inventory since the atmosphere responds to the net balance of all CO_2 emissions and removals (i.e. carbon stock losses are functions of the carbon stock gains accumulated across time as well as carbon stock gains are functions of the carbon stock losses from the land associated with the activity previously occurred, which has in practice, caused a rejuvenation of the carbon pool).

However, countries may be interested in monitoring and reporting GHG fluxes from specific human activities that can impact a fraction of the national land use (e.g. forest conservation over a fraction of the entire forest estate) or impact more than a single land-use category across time (e.g. deforested land to cropland) or, finally, that have a limited time frame. In any case and for any activity, the symmetry principle applies and both gain and losses shall be monitored and reported.

Where multiple activities impact the same unit of land, the same problem of attribution that brought the IPCC to opt for a land-based categorisation of sinks and sources again becomes relevant. Thus, although the reporting framework could be activity-based, segregation of activities among lands or land-based reporting of the net result of all activities occurring in any unit of land is the way to ensure an accurate quantification of what the atmosphere experiences as a result of the activity(ies), and therefore to achieve full consistency among the activity(ies) reporting and the national GHG estimates.

The description of REDD+ activities and the discussion of the use of IPCC methods to estimate emissions and removals associated with them (**Section 2.5**) lead to the activity data requirements specified in **Table 5**.

Table 5: Major activity data requirements for REDD+ activities

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, Wetlands, Settlements, Other Land)
3	Annual transfer from primary forest to modified natural forest and to 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 of modified natural forest within managed land

a. These are the forest types used in the methodological discussion because they correspond to FAO FRA reporting. Countries may adopt any other stratification that suits national circumstances (e.g. modified natural forest may also be reported as secondary forest).

Box 12: 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; and (e) enhancement of forest carbon stocks. The GPG2003 refers to six land-use categories , namely Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. The relationship between REDD+ activities and IPCC land-use categories is as follows:

- Deforestation is an activity that converts forest land to other land-uses (i.e. forest land converted to cropland, forest land converted to managed grassland, forest land converted to managed wetlands, forest land converted to settlements, forest land converted to other

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to national circumstances (see 2006 IPCC Guidelines).

land).

- Degradation, conservation of forest carbon stocks, and sustainable management of forests are activities that occur within forest land that is not converted to any other land uses, but remains forest land.
- Enhancement of forest carbon stocks can occur either within forest land that remains as forest land or by converting other land-uses to Forest Land (i.e. cropland converted to forest land, managed grassland converted to forest land, managed wetlands converted to forest land, settlements converted to forest land, other land converted to forest land).

The 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. Countries may wish to depart from the above approach for three reasons. Firstly 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 which 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 shall ensure that the REDD+ emissions and removals estimates and the estimation of the FREL and/or FRL use the same methods (**Section 2.5**) and that emissions and removals from any land is not counted more than once although a land can host more than one REDD+ activity.

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 the 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 the 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 categories to allow transparent and consistent reporting, where a land under REDD+ activities has a use different from that of the corresponding IPCC land-use category;
- establish and document reporting rules that describe under which land-use categories emissions and removals will be reported.

Countries should ensure that tracking of lands between IPCC land-uses categories and/or REDD+ activities does not lead to bias estimates of emissions or removals (e.g. by selective inclusion or exclusion or by partial reporting of carbon stock changes). Further advice on full tracking of lands and events that lead to multiple land-use changes or REDD+ activity through time is provided in **Chapter 5**.

2.3.3 Stratification

Once land use and land use conversion areas have been identified and quantified, it is necessary to consider the capacity and need for further stratification. Stratification is the process of disaggregating a land-use category (e.g. Forest Land, Cropland, Grassland) into logical, typically homogenous sub divisions (e.g. tropical/dry forest, crop types, improved or unimproved pastures). This process is commonly applied to reduce the cost of field inventories. Stratification can also reduce the uncertainty of emissions and removals estimates as it is useful to (IPCC, 2019):

- estimate emissions and removals for key land-use sub-categories;
- enable tailoring of specific methods or data collection processes in different strata. For example, due to weather conditions and cloud effects, it is much more difficult to measure Forest Land converted to other land uses using multispectral remotely sensed data in fragmented dryland forests than contiguous moist tropical forests;
- track areas under conversion across time series, especially to deal with subsequent changes;
- assist in the management of uncertainties and plan continuous improvement of the inventory; and
- increase flexibility in the reporting of monitored data, such as the effectiveness of policies tailored to specific strata (e.g. forest types, risk types).

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 (see **IPCC 2010 Technical Paper Revisiting the Use of Managed Land as a Proxy for Estimating National Anthropogenic Emissions and Removals).** The GPG2003 assumes that all emissions and removals on managed land are anthropogenic. 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 generally 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 specialised map layers, such as soils, site class, topography, aspect, dominant tree species or species clusters are commonly used for stratification. However, unless all land use area and stratification data are spatially-explicit (Approach 3), the development of rules for allocations to strata may be required (IPCC, 2019). 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+(53) may require finer resolution data (both spatially and temporally) than are currently being used by countries. Development of national capacity will help to take advantage of technical developments as they become available (e.g. it is currently challenging to detect changes in canopy cover associated with degradation). As such, auxiliary information on harvesting, whether legal or not, and other disturbances may help considerably with classifying degraded areas from remotely sensed data. The likelihood of human disturbance can also be the basis for stratification. Identification of areas at high risk of deforestation

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(53) Namely conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks.

can assist in designing **early warning systems**.

In this context, countries may find that national land classifications change over time as national circumstances change and more detailed activity data and emissions/removals factors become available. In some cases, the stratification will be elaborated with the addition of more detailed emissions and removals factors. In other cases, new stratification systems will be established when countries implement new forest inventories or changes to processing of remotely sensed data. When changes to the stratification system occur, countries should maintain **time series consistency** by recalculating the entire time series of estimates using the new stratification.

2.3.4 Methods

The IPCC distinguishes between two methods for estimating emissions and removals of CO_2 associated with annual rates of change in all carbon pools. These are:

- the gain-loss method(54) (which estimates annual emissions and/or removals separately and directly from the processes to which those are associated); and
- the stock-difference(55) 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).

IPCC methods are applied at the level of the different **carbon pools** within identified strata and the emissions and removals summed. The carbon stock estimates for the stock-difference method are commonly estimated from repeated field measurements of forest variables as part of an NFI (**Section 3.2.1**) or equivalent survey data. The IPCC notes that the stock-difference method provides good results where there are relatively large increases or decreases in estimated biomass, or where there are statistically rigorous **NFIs.**(56) Since countries may not possess an NFI, or may not possess an NFI with suitable statistical design, and NFIs by themselves do not track or map REDD+ activities, the advice in the MGD focuses more on the gain-loss method, noting that the gain-loss method requires ground data which can come from an NFI.

The gain-loss method estimates annual net emissions or removals of CO_2 from a carbon pool as the sum of gains and losses occurring across the year. This may be achieved by the use of carbon-stock-change-factors, hereafter simply referred to as emissions/removals factors, and activity data, or by the use of more sophisticated representative models and integrated systems (**Section 2.4**). Most of what follows relates to the 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).(57) 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 come from remotely sensed data and correspond to strata based on forest type and condition, management practice or disturbance history. **Auxiliary data** can support confirmation

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(54) For the gain-loss method, see **Equation 3.1.1 in the GPG2003** or **Equation 2.7 in Volume 4 of the 2006 GL**.

(55) The stock-change method is called the stock-difference method in the 2006GL. For the stock-(difference-)change method, see **Equation 3.1.2 in the GPG2003** or **Equation 2.8 in Volume 4 of the 2006GL.**

(56) See **page 3.25 of the GPG2003**, or **page 2.13 in Volume 4 of the 2006 GL.**

(57) REDD+ activities are identified in **paragraph 70 of decision 1/CP.16.**

of such strata.

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 density 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 stock as the difference between the annual net(58) increment due to growth and the annual decrease due to losses from processes such as commercial harvest, fuel wood removal(59) 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 that have, ideally, been located within the activity data classes of interest using a probabilistic design. Care should be taken when using data obtained from research or other plots, as they might not characterise the class, as the method assumes.

The choice between using a gain-loss or stock-difference method at the appropriate Tier(60) will depend on expert judgment, taking the status of national inventory systems and forest characteristics into account. **Figure 3** summarises 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

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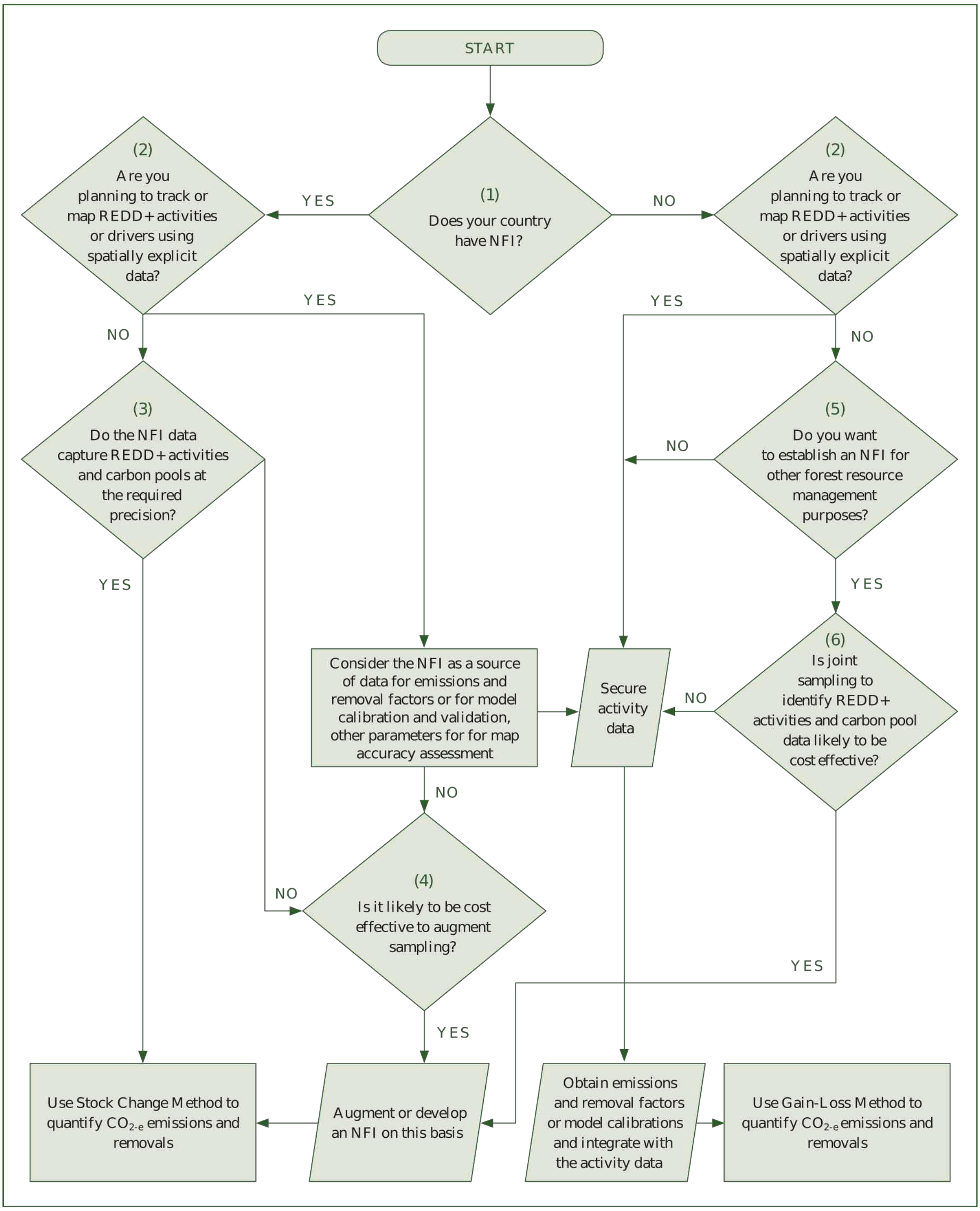
(58) Net of mortality.

(59) Other auxiliary data such as log input to processing plant together with an estimate of intermediate losses may also be relevant.

(60) Because of the data requirements the stock-difference method is not appropriate at Tier 1.

complementary.

Figure 3: Method selection for estimating CO_2 emissions and removals based on available data



Considerations for the decision points in the tree are as follows:

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

An NFI is a periodically updated sample-based system covering all lands 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 emissions and removals 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 optimised 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 are 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 emissions/removals factor data from IPCC guidelines and guidance (Tier 1), or nationally-relevant data from sampling, forest inventories or in combination with other ground data such as intensive research sites (Tiers 2 or 3); noting **considerations for using existing data**. 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 (e.g. 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.

2.3.5 Approaches

The IPCC describes three approaches to consistent representation of lands (**Box 13**):

- **Approach 1 -** is not spatially-explicit(61) and simply uses net areas associated with land use.

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(61) 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-

- **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.

Remotely sensed data are likely to be used to greatest advantage with Approaches 2 and 3. Most countries reporting REDD+ will need at least Approach 2, with most aiming for Approach 3 enabling geographically explicit tracking activities and drivers, to support estimation of GHG emissions or removals, and in the context of results-based finance and to facilitate benefit-sharing mechanisms.(62) This may have consequences for **consistency with the national GHGI** that need to be considered in setting **goals and scope** during the design phase of the NFMS.

Approaches 2 and 3 provide different levels of detail, therefore methods for estimating emissions and removals (i.e. gain-loss or stock change) need to be tailored to the available land-use data. When considering how to apply methods for estimating GHG emissions and removals using activity data from different Approaches, it is important to differentiate between:

- emissions and removals that occur in the year of the activity, such as fire or biomass loss from harvesting or clearing of land and emissions from drainage of organic soils and removals from forest growth; and,
- lagged emissions/removals that may occur for years after an activity or change in land-use occurs, such as forest regrowth, decay/accumulation of soil organic matter or decay of carbon stock in forest products.

Approach 2 data allow for the use of estimation methods that account for emissions and removals both in the year of the activity and also lagged emissions and removals from past activities. Approach 2 data can be used with any combination of Tier 1 and 2 emissions factors or Tier 3 models. Approach 2 does not allow for the tracking of multiple changes (>2) in land use on a single land unit through time. As such, when using Approach 2 it is good practice to stratify land into appropriate age or condition classes that can deal with these issues. For example, when using Tier 1 methods in forest land, stratifying into young forest land (less than 20-years) and mature forests (older than 20-years) can enhance the accuracy of the estimate of a land-use change occurring in forest land. Similarly, a stratification into forest types or condition classes can enhance the accuracy of GHG estimates, since the conversion of a mature forest typically results in higher carbon stock losses and associated GHG emissions than the conversion of a young, heavily disturbed or plantation forest.

Approach 3 uses the time series of data for land units to capture multiple changes in land-use and can be applied with any Tier estimation methods, noting that the combination of Approach 3 and Tier 3 can increase the complexity of modelling systems for estimating emissions and removals. While it is possible to use different emissions estimation methods in spatially-explicit approaches, it is important to ensure that all the estimation methods are applied consistently. For some carbon pools, such as biomass, using different methods and models for different land uses or sub divisions of land use (e.g. forest type) will not create any inconsistencies. However, other pools, in particular soil carbon, require that the estimation methods be consistent. For example, if two or more methods are used for estimating soil carbon changes for different land-uses, then the stocks and estimated stock changes need to be handled consistently when the land-use changes. Where multiple methods are applied for estimating changes in carbon stocks within and between land-uses it is good practice to describe how these models work consistently across land-uses. For Approach 3 gain-loss methods, the quantity of information on land-use and change through time often makes it difficult to use spreadsheets to

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to-wall remotely sensed data.

(62) As such advice on Approach 1 is not covered in the MGD. Refer to **Volume 4, Chapter 3, of the 2019 Refinement** (IPCC, 2019) for information on Approach 1.

calculate emissions and removals. Advanced methods using integrating tools (Brack *et al.*, 2006; Kurz and Apps, 2006) are typically used in such circumstances. These tools estimate emissions and removals for each uniquely identified land unit, assign the land unit to an IPCC land-use category, then sum the results for reporting.

Box 13: Approaches to consistent representation of lands

- **Approach 1 -** Represents land use area totals within a defined spatial unit, which is often defined by political boundaries, such as a country, province or municipality.
- **Approach 2 -** The essential feature of Approach 2 is that it provides an assessment of both the gross losses and gains in the area of specific land-use categories and what these conversions represent (i.e. changes both from and to a category). Thus, Approach 2 differs from Approach 1 in that it includes information on conversions between categories, but is not tracking those changes across time.
- **Approach 3 -** The key defining characteristic of Approach 3 is that it is both spatially and temporally consistent and explicit. Sample-based, survey-based and wall-to-wall methods can be considered Approach 3, depending on the design of the sampling/mapping program and the way the data are processed and analysed.

See **Chapter 2 of the GPG2003**, or **Volume 4, Chapter 3 of the 2006GL**.

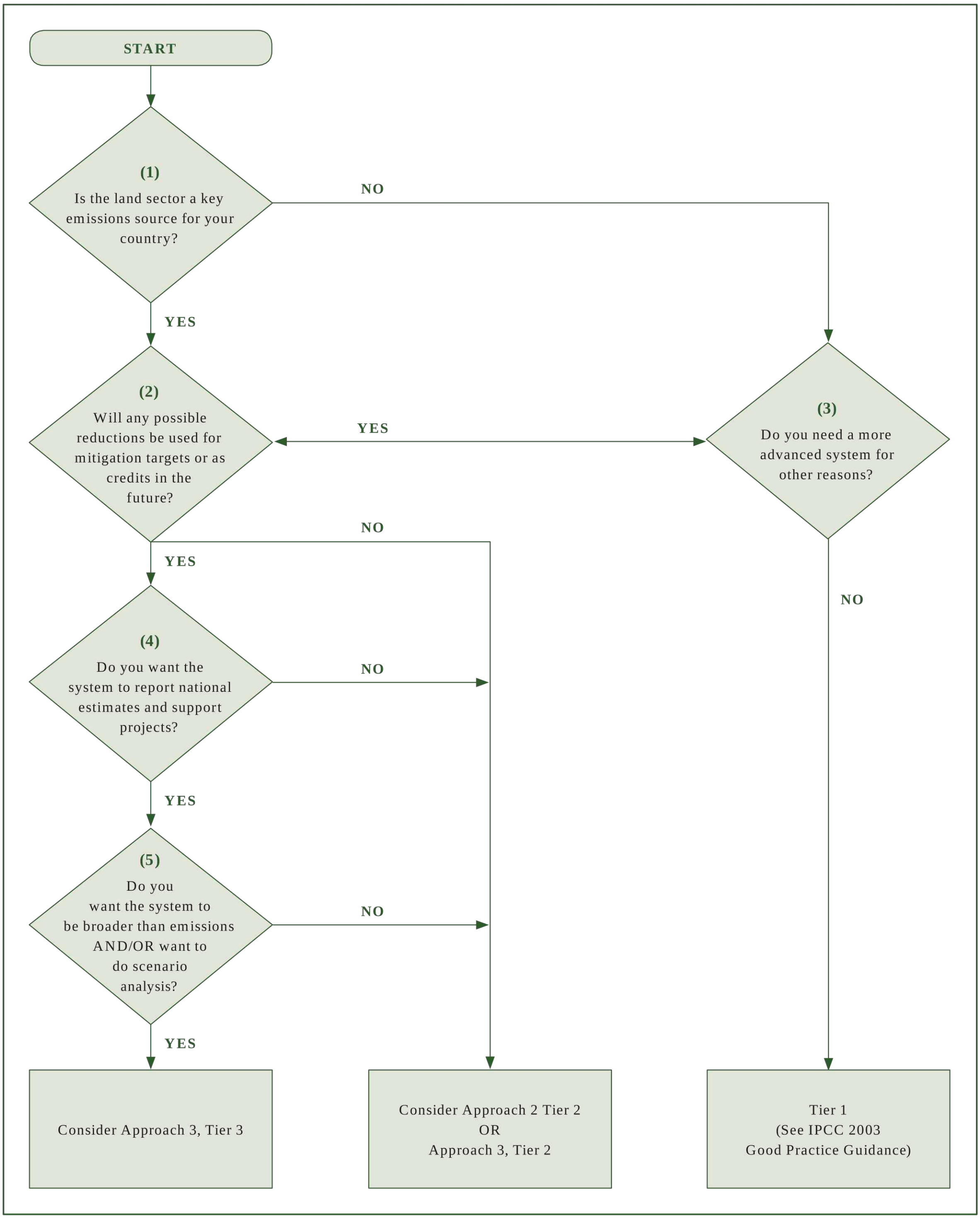
2.3.6 Tiers

The IPCC describes methods at three levels of detail, called tiers, noting that changes in carbon stocks can be estimated using emissions factors (Tier 1 and 2), models (Tier 3 gain-loss methods) or direct measurements (Tier 3 stock difference), or any logical and consistent combination of all three. **Box 14** summarises 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 using data specific to their national circumstances. This would typically require **ground based observations** to estimate the values required if they do not exist. Tier 3 methods are generally more complex, normally involving modelling and finer resolution land use and land-use change data. The IPCC expects that higher Tier (meaning Tier 2 or Tier 3) methods will be applied for **key categories**, unless the data collection to do this would significantly jeopardise resources required for other key categories, in which case Tier 1 estimates can be provided.

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. 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 operational 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 models use Tier 1 or 2 methods for on-going emissions of soil carbon following deforestation.

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. Selection of Tiers and Approaches may also be influenced by the requirements of results based payment facilities and associated benefit-sharing mechanisms. A summary of the key factors to consider is provided in the form of a decision-tree in **Figure 4**. Cost-effectiveness is discussed in **Section 1.3**.

Figure 4: Key factors relevant to system design, tier and approach selection in GHG estimation



Considerations for 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 (**Section 2.3.9**). 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 the **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 an 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?

Subnational 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 Decision Point 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.

Box 14: The IPCC tier concept

A tier represents a level of methodological complexity (IPCC, 2003; IPCC, 2006; IPCC, 2019). Three tiers are provided. Tier 1 is the basic method, Tier 2 intermediate and Tier 3 most demanding in terms of complexity and data requirements. Tiers 2 and 3 are sometimes referred to as higher tier methods and are generally considered to be more accurate.

Tier 1 employs the method described in the IPCC Guidelines using country specific activity data and the default emissions/removals 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 remotely sensed data. The stock-difference method is not applicable at Tier 1 due to data requirements (GPG2003).

Tier 2 generally uses the same methodological approach as Tier 1, but applies emissions/removals 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 emissions/removals factors and parameters for specific regions and specialised land-use categories.

Tier 3 includes models and can utilise 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, integrating 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 the cost of an increase in the complexity of measurement processes and analyses. Lower Tier methods may be combined within higher Tiers for those pools that 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 Tier 3 directly than to produce a Tier 2 system that then needs to be replaced. For example, where detailed forest inventory data are available, it may be possible to develop empirical growth curves from these data almost as easily as developing emissions/removals factors.

2.3.7 Pools and gases

The **GPG2003** provides methodologies to estimate changes in five carbon pools (above-ground biomass, below-ground biomass, dead wood, litter, and soil organic matter(63) (**Table 6**) and non-CO_2 GHG emissions (i.e. CH_4 and N_2O **for six land-use categories**), and for changes between land-use. It is good practice to report total net changes within all carbon pools across the six land-use categories. Changes in carbon pools **identified as key** should be estimated using National data (i.e. higher order Tier 2 or Tier 3 methods). In the absence of national data to facilitate higher order estimates, countries should apply Tier 1 default methods and factors presented in the IPCC guidelines and guidance. Application of Tier 1 methods would hold preference over the exclusion of significant pools.

Table 6: Carbon pool definitions

Pool		**Description**[a]
Biomass	Above-ground biomass Below-ground biomass	All living biomass (expressed in tonnes dry weight) above the soil, including stem, stump, branches, bark, seeds, and foliage.[b] All living biomass of live roots. Fine roots of less than (suggested) 2 mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.
Dead organic matter	Dead wood Litter	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. 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 **Chapter 3, Table 3.1.2, GPG2003**. The corresponding carbon pool definitions used in the 2006 Guidelines are found in **Volume 4, Chapter 1, Table 1.1**.

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

b. 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

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(63) The GPG2003 also provides three alternative methods for dealing with harvested wood products.

consistent manner throughout the inventory time series.

The gases to be reported for the AFOLU sector are:

- **carbon dioxide (CO_2) -** from changes in the organic matter stored in five carbon pools as a result of management disturbances and land-use conversions;
- **methane (CH_4) -** from drainage of peat soils and from prescribed or wildfires in managed forest land or in forest land converted to other land uses;
- **nitrous oxide (N_2O) -** from drainage of peat soils and from prescribed or wildfires in managed forest land or in forest land converted to other land uses.

Methods and default emissions factors for non-CO_2 gases are listed in the sections related to **soil carbon** and **emissions from prescribed fires and wildfires.**

2.3.8 Time series consistency and recalculations

The time series is a central component of the GHGI (and REDD+ estimates) because it provides information on historical emissions trends and tracks the effects of actions to reduce emissions (IPCC, 2006). Both methodological changes and refinements, as well as improvements in data sets(64) over time, are an essential part of improving inventory quality and must be pursued. However, using different methods and data in a time series could introduce bias because the estimated emission trend will reflect both real changes in emissions or removals and the pattern of methodological changes. Therefore, when changes, refinements or improvements are made it is good practice to recalculate the entire time series (IPCC, 2006; IPCC, 2019).

Recalculation of the entire time series can be triggered by a range of issues (**Box 15**). The development of inventory methods and interpolation/extrapolation tools (models) for the agriculture, forestry and other land use sector (AFOLU) is still ongoing (IPCC, 2019). Thus, it is anticipated that recalculation in the AFOLU sector will continue to be significant as new technology and data sets drive improvements in, for example, land use classification.

There are both simple and complex scenarios that can trigger recalculation of the time series. In simple cases, sampling or experimentation may lead to the replacement of default emissions factors with country-specific ones, triggering a time series recalculation. It is also likely that updates in maps and activity data will lead to changes in multiple land-use categories or REDD+ activities, even if the improvement targeted only one category. In such case GHG estimates of all the land-use categories and activities need to be recalculated accordingly.

Generating a complete and consistent time series triggered by a change or refinement can be difficult where data are missing for one or more years. The IPCC outlines a number of splicing techniques,(65) such as overlap, surrogate data, interpolation and trend extrapolation and non-linear trend analysis, to combine or join more than one method/data set to form a complete time series. The choice of splicing technique involves expert judgement and is dependent on the availability of data for two overlapping methods, the adequacy and availability of surrogate data sets, and the number of years of missing

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(64) A methodological change in a category is a switch to a different tier from the one previously used. Methodological changes are often driven by the development of new and different data sets. This is in contrast to a methodological refinement which occurs when an inventory compiler uses the same tier to estimate emissions but applies it using a different data source or a different level of aggregation.

(65) Splicing techniques can be used together if it is not possible to use the same method or data source in all years. These techniques are described in detail in the **Volume 1, Chapter 5.3.3, of the 2019 Refinement** (IPCC, 2019).

data. Where there are large gaps in input data (for example, maps only every 5-years), the methods below are typically applied to interpolate between measurement periods. **Table 7** summarises the requirements for the applicability of each technique and suggests situations in which they may or may not be appropriate. Countries should use **Table 7** as a guide rather than a prescription as the best method will depend on country circumstances.

Table 7: Examples of the application of splicing techniques

Splicing Technique	Applicability	Comments
Overlap	Data necessary to apply both the previously used and the new method must be available for at least one year, preferably more.	Most reliable when the overlap between two or more sets of annual estimates can be assessed. If the trends observed using the previously used and new methods are inconsistent, this approach is not good practice.
Surrogate data	Emission factors, activity data or other estimation parameters used in the new method are strongly correlated with other well-known and more readily available indicative data.	Multiple indicative data sets (singly or in combination) should be tested in order to determine the most strongly correlated. Should not be done for long periods.
Interpolation	Data needed for recalculation using the new method are available for intermittent years during the time series.	Estimates can be linearly interpolated for the periods when the new method cannot be applied. The method is not applicable in the case of large annual fluctuations.
Trend Extrapolation	Data for the new method are not collected annually and are not available at the beginning or the end of the time series.	Most reliable if the trend over time is constant. Should not be used if the trend is changing (in this case, the surrogate method may be more appropriate). Should not be applied for long periods.
Non-linear Trend Analysis	In cases where time series consistency is best represented by multiplicative (exponential) rather than additive (linear) relationships.	Most reliable for trend analysis of model outputs. Applicable in the case of large annual fluctuations with observed high standard deviations (see **Volume 1, Chapter3, Box 3.0a of the 2019 Refinement** for guidance on standard deviation values).
Other Techniques	The standard alternatives are not valid when technical conditions are changing throughout the time series (e.g. due to the introduction of mitigation technology).	Document customised approaches thoroughly. Compare results with standard techniques.

For the land sector, in particular when using remotely sensed data, the techniques in **Table 7** need to be considered in both the system design process and the ongoing updating and operation. Splicing techniques require a sufficient time overlap of the two methods. Moving from one technology or method to the next without any overlap can introduce errors that cannot be easily estimated.

For REDD+ activities, it is also important to consider the effect of recalculations on agreed baselines and targets, especially where these are part of a payment scheme. This is a complex policy area and no guidance is provided here, other than to note the potential issues under REDD+ payment schemes and consider them in system update processes.

Box 15: When should methods be changed or refined or should new categories or gases be added?

The IPCC considers it is good practice to change or refine methods when:

- Available data have changed
- The previously used method is not consistent with the IPCC Guidelines for that category
- A **category has become key**
- The capacity for inventory preparation has increased
- New inventory methods become available
- Availability of new emissions/removals factors in the IPCC Guidelines that could be different from previous IPCC Guidelines
- Correction of errors

A country may add new categories or new gases to the inventory when:

- A new emission or removal activity is occurring
- Rapid growth is experienced in a very small category
- New IPCC categories are introduced
- Country-specific categories are identified but not covered by the 2006 IPCC Guidelines and its 2019 Refinement (e.g. CH_4 emissions from and removals by agricultural soils or forest ecosystem in low forest cover countries).
- Additional inventory capacity is realised

For more specific examples, refer to **Volume 1, Chapter 5.2, Box 5.1, in the 2019 Refinement** (IPCC, 2019).

2.3.9 Key category analysis

Key category analysis (KCA) is the IPCC's method for allocating priorities for resource allocation to categories of the GHGI. Key categories are those that, when summed together in descending order of magnitude, add up to 95 percent of the total. KCA is described in **Section 5.4 of GPG2003**, and **Volume 1, Chapter 4 of the 2006GL**. Key category analysis can be used to identify significant carbon pools (and activities). Since it is not known at the outset of a GHGI which categories are key, and which accordingly need to be prioritised in the allocation of available resources, KCA may initially need to be undertaken using Tier 1 methods.

REDD+ activities are mostly not recognised categories in the IPCC inventory methodology, but in the case of deforestation, the GPG2003 requires adding up all GHG emissions and removals, in absolute terms, associated with conversions of forest to other land uses, and treating deforestation as key if the result is larger than the smallest category considered to be key using the UNFCCC reporting categories. The IPCC also provides qualitative criteria for identifying key categories, one of which is that categories for which activities are implemented for reducing emissions, or enhancing removals, 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.

In applying KCA,(66) the GPG2003 guides the identification of significant subcategories that shall be considered as key. Significant subcategories are those that contribute at least 25 to 30 percent of the emissions or removals in the parent category to which they belong. This does not mean that non-significant subcategories may be omitted, although these countries may use Tier 1 methods if country specific data are not available. Identifying significant subcategories assists in the allocation of resources to collect country specific data and in focusing efforts to reduce uncertainties.

The subcategories defined in the GPG2003 (see **Table 3.1.3, page 3.20)** to be tested as significant are for each land-use category: biomass, dead organic matter, soils, for CO_2; fire, soil organic matter mineralisation, nitrogen inputs, cultivation of organic soils, for N_2O; fire, for CH_4.

Decisions 12/CP.17 and **13/CP.19** say that significant pools and activities should be included in FRELs 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 percent or more of the GHG emissions or removals associated with a REDD+ activity. Other percentage levels could be used to define significant; (e.g. the **FCPF Methodological Framework** uses 10 percent). The analogy is not exact because the IPCC uses the 25 to 30 percent 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 the 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, would be to develop a set of rules to help ensure a consistent policy signal to prioritise the most relevant sources/sinks. 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.

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(66) As set out in **Section 3.1.6 of GPG2003** the decision trees provided by GPG2003.

- 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 prioritisation 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 summarised 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.

Significance of each reported REDD+ activity could be considered in the same way as carbon pools. Activities likely to be affected by displacement due to action related to the most significant activity would be considered potentially significant, for inclusion at the same time as the most significant activity, or for prioritisation in a stepwise approach as better data become available. 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.

2.3.10 Attribution

Attribution is the process of associating observed land cover and cover changes with land use and land-use change (**Box 16**). Because different management and disturbance types have different impacts on carbon stocks and GHG emissions (Kurz *et al.*, 2009), knowledge of the cause of disturbance is needed not only to estimate areas of land use and land-use change but also to estimate the associated GHG emissions and removals (IPCC, 2019).

While two dates of satellite imagery may be useful for quickly depicting land cover change, identification of permanent land-use changes may require more data and analysis. It is therefore good practice to ensure that all land cover changes identified by satellite data are verified using sufficient spatial and temporal resolution imagery, ground reference and other auxiliary data sets to isolate permanent land-use change from that of temporary loss of forest cover (**Table 8**). This process, referred to as attribution of satellite derived land cover change, helps to identify human induced land-use change and to allocate land-cover change to the underlying cause of disturbance and to assign lands to the IPCC land-use categories through time. 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). These data sets are combined to develop attribution rules to estimate the likely cause of the disturbances that resulted in the observed land-cover changes, based on their spatially-explicit location.

Table 8: Examples of auxiliary data and assumptions for classifying land use

Data	Source	Possible assumption
Forest management plans	Forest agencies, stakeholders	That plans are implemented.

Data	Source	Possible assumption
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 soil types	Resource agencies, meteorological agencies	Determine the types of crop and management that can occur in certain regions (e.g. no crops in a desert).

The auxiliary data and assumptions need to be reviewed frequently as part of the inventory process. Further, as more data becomes available through time (e.g. more up to date cover maps) it is likely that the attribution of a change will vary as in some cases the assumptions will not hold. For example, where cover is lost in a known productive forestry area, the emissions may be attributed to forest harvesting and as such not counted as deforestation/land use change. However, if 5 to 10-years later the cover has not returned, then the area may be considered to have changed land-use. In this case the area will need to be moved to the converted category in the year the cover was lost and the time series will need to be recalculated. This is common practice in many national inventories (**Section 2.3.8**).

Useful auxiliary data sets in support of attribution include, but are not limited to, past and current land cover, management practices, fire, flooding and cyclone. **Volume 4, Chapter 3, Box 3.1a, in the 2019 Refinement** (IPCC, 2019) presents some useful examples of assigning land use and land-use change categories in What results is a set of country-specific decisions on a series of reporting rules which can also be applied to categorise land-use change. These rules should be documented and transparently communicated to enable the consistent generation of land-use change data (activity data) through time.

Box 16: Monitoring plantation management in Kenya

In Kenya, the standard public plantation forest management practice following harvest is to put crops on the land for 1 to 2-years before replanting. In this case, the land classification program will correctly report that the land 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 public plantation forest (determined through specified shapefiles that define public plantation forest areas). 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 are reported under forestland. However, there is also the chance that the harvested land does not revert into a forest in several subsequent mapping years and in this case a land-use change is considered to have occurred at the time of harvest and the land areas are updated accordingly (**Section 2.3.8**).

2.3.11 Definition of forest

A forest definition is needed 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/FRL should be the same as that used subsequently by the NFMS for all MRV purposes. For example, exclusions from the forest definition, such as for oil palm plantations or mangroves, should be applied consistently over time.

No single definition of forest has been agreed under the UNFCCC for Forest Lands. In the context of REDD+, 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 organisations, to explain why, and why the definition was used in the construction of FREL/FRL. This indicates an expectation that:

- the forest definition used for REDD+ will be the same as that used for previous reporting on forests;
- that other reporting will be updated to reflect any new definition; or
- reasons for having different definitions are transparently explained.

In considering forest definitions, the NFMS may wish to note that 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. The 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).

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 percent 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 to 30 percent or tree height of 2 to 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”. 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 percent, 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. The Cancun Agreements specify that REDD+ mitigation actions should not incentivise 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.

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 to occur predominantly on managed land,(67) and therefore those on land remaining unmanaged are not reported unless unmanaged land is subject to land-use conversion.(68) According to the 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".(69) Given this broad definition of managed, it is entirely possible that countries may have little or no land considered unmanaged and that what is considered managed may differ from country to 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. They should be applied consistently over time; otherwise there is a risk that apparent changes in emissions or removals will reflect differences in the way that definitions are applied, rather than the effect of, for example, REDD+ interventions. 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 remotely sensed data) are being used together. How consistency is achieved could usefully be reported under MRV provisions.

Some particular issues to consider in the adoption and application of forest definition thresholds in the content of remotely sensed observations include:

- determination of forest boundaries in fragmented landscapes (relevant to minimum area);
- determination of crown cover;(70)
- determination of height; and
- determination of minimum width (where used as a threshold criterion).

On the one hand, there may be a policy position to capture as much of the forest areas as possible in the Forest Lands category, so the thresholds are set low (e.g. 10 percent canopy cover and 0.5 hectares); on the other, practically monitoring 10 percent canopy cover with freely available medium resolution imagery may be problematic and lead to increased error and higher reported uncertainties.

When using a structural definition of forest (canopy cover, minimum area and height) some practical things to consider may include:

- The detection limit of the sensor being used (e.g. 10 percent is often difficult to discriminate using medium resolution satellite data, while 20 or 30 percent is likely to produce more accurate estimates).
- Any effect of the thresholds on activity rates (e.g. lower forest canopy threshold) will raise forest area but not necessarily deforestation rates (i.e. if there are a few trees left in the landscape, the

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(67) See discussion on the use of managed land as a proxy for anthropogenic effects in **2006GL Volume 4 page 1.5.**

(68) Carbon stock changes and greenhouse gas emissions on unmanaged land are not reported under the IPCC Guidelines, although reporting is required when unmanaged land is subject to land-use conversion. See **GPG2003 Chapter 2, page 2.5.**

(69) The 2006 GL says 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 national level, described in a transparent manner, and be applied consistently over time.

(70) For example, Magdon and Kleinn, 2012. Uncertainties of forest area estimates caused by the minimum crown cover monitoring. Environment Monitoring and Assessment 185(6): 5345-5360.

canopy cover definition will trigger forest degradation rather than deforestation)

In establishing a national forest definition, it is also 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 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 emissions/removals 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 a set rules to ensure that lands are correctly categorised 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.

A country can change the forest definition thresholds where it is considered a methodological refinement to improve the quality of reporting and still meet IPCC good practice, as long as an explanation is provided and the new forest definition is adopted consistently across other reporting. In such cases, the IPCC considers it good practice to conduct the recalculation on the entire time series of emissions, not just the most recent years. Both methodological changes and refinements over time are an essential part of improving inventory quality.

The 2019 Refinement anticipates that the use of recalculation techniques in the AFOLU Sector will be particularly important. The development of inventory methods and interpolation/extrapolation tools (models) for this sector is ongoing and it is anticipated that changes (and refinements) to the methods of many countries will occur over time due to the complexity of the processes involved (**Volume 1, Chapter 5, Time Series Consistency**).

The Refinement offers good practice related to splicing techniques which can be applied to combine or join more than one method to form a complete time series, where it is not possible to use the same method or data source in all years. Guidance is presented to minimise potential inconsistencies in the time series. Countries should provide documentation of any splicing techniques used to complete a time series. The documentation should identify the years in which data for the method were not available, the splicing technique used, and any surrogate or overlap data used.

Finally, it is recommended to consider the definitions used for other IPCC land use categorisations (i.e. Croplands, Grasslands, Wetlands, Settlements and other) when developing a forest definition. Failing to do this can lead to inconsistencies in the overall inventory reporting for the AFOLU sector. This is particularly the case for areas of forest land that have been cleared to other land uses or where land has been converted to forest, as these need to be placed into the appropriate IPCC land-use category (e.g. Forest Land converted to Grassland, or Cropland converted to Forest Land). Achieving this consistency will often require collaboration with other government agencies, such as those dealing with agriculture (**Chapter 1**).

2.4 Integration frameworks for estimating emission and removals

Developing systems for reporting greenhouse gas emissions and removals and their uncertainties in accordance with IPCC good practice requires the combination of data from different sources, with data gaps filled through assumptions and expert judgement where necessary (**Box 17**). Tools to facilitate this are known as integration frameworks. Integration frameworks can help to organise data and estimation methods at any level of methodological complexity and facilitate the systematic progression from simpler to more complex methods. Integration frameworks that are designed to simulate the impacts of human activities on future carbon stock changes can also support the development of scenarios relevant to policy analyses.

Ideally, an integration framework should be scalable and apply to forest stands, projects, regions or countries to support **multiple goals**. 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.

The **Approach**, **Methods** and **Tier** adopted by the NFMS have implications for subsequent integration of data to estimate emissions and removals to meet defined MRV objectives. There are two main methods for integrating remotely sensed and ground-based observations:

1. The activity data x emissions/removals factor frameworks (generally representative of Tier 1 or Tier 2 methods).
2. Fully integrated frameworks, with two sub-cases:
    - Spatially-referenced models (representative of Tier 3, Approach 2/3 methods).
    - The spatially-explicit methods (representative of Tier 3, Approach 3 methods), which track individual units of land (polygons or pixels) across time.

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 when they are correctly implemented and capable of representing the population of interest (IPCC, 2019) because:

- they do not have to deploy simplifying assumptions inherent in emissions/removals factor based approaches; and
- 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 also increase in terms of information to be handled for a transparent report, as a consequence.(71)

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. However, it

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(71) Transparency is not just about being simple. Complex models are transparent when all information to describe them is provided, as well as to understand their outputs. This can also be achieved with Tier 3 methods; see for instance **https://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf**

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, an 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,** the spatial scope of the integration framework can be expanded. Well-designed frameworks should be able to accommodate an increase in estimation complexity and data richness.

Integration frameworks typically require knowledge of:(72)

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 (e.g. dead organic matter, soils).

These data, in particular the data on land cover, land-cover change and the agents of change, are increasingly obtained from remote sensing. They can greatly assist in describing the history of land-cover changes that drive emissions and removals. The further back in time that these data go on a consistent basis (see **Box 30**), the more reliable and useful they are as inputs to the integration tools. Additionally, integration frameworks can generate **total uncertainty for estimates** through either propagation of error or Monte Carlo simulations, both IPCC methods for generating total uncertainty.

The analysis of the impacts of future REDD+ interventions (or forest management scenarios more generally) can be undertaken with integration frameworks 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 remotely sensed 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 percent 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 alternative future management regimes can allow for the evaluation of various climate change mitigation strategies (Smyth *et al.*, 2014). To ensure consistency, it is recommended that when projecting forward estimates of REDD+ activity rates, the methods and data used are consistent with those used in monitoring.

Box 17: 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

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(72) The points listed are most relevant for integration frameworks based on gain-loss approaches.

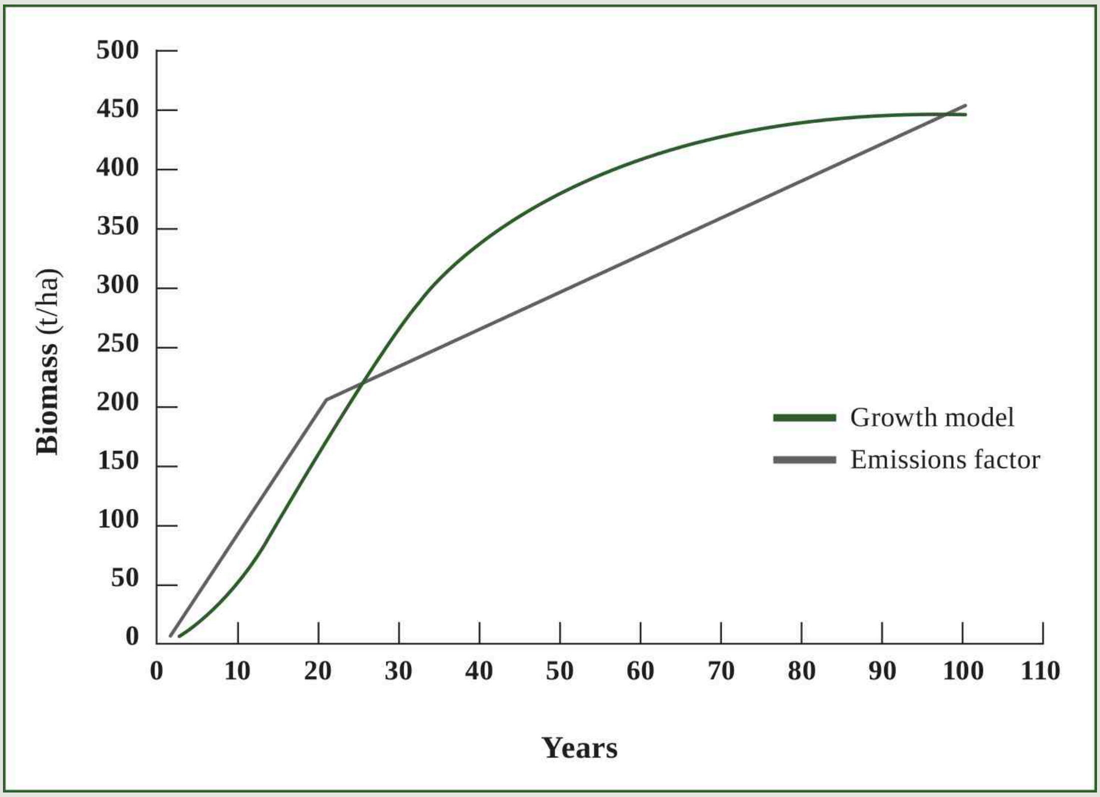
derived data have errors associated with the model, in addition to measurement errors.

- **Assumptions -** To convert input data into values that can be used in emissions estimation may require assumptions. For example, IPCC default 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. In reality, growth will also vary year to year, based on weather conditions and past disturbances. The degree to which these effects will be included in the estimates depends on the model form chosen (e.g. empirical or process based models). 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 on 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 annual accuracy in emissions estimates across the time series (Figure 10). 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, forest inventory data from ground and plot measurements, and data from intensively monitored sites with models. Models can help to 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**) to stand alone executables (e.g. **ALU** and the **IPCC GHG Inventory software**) and detailed analytical systems (e.g. **CBM-CFS3**, **FullCAM**, **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. **Figure 5** 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 on emissions/removal estimates over short periods.

Figure 5: Comparison of an emissions/removals factor model and a typical growth curve



2.4.1 Activity data x emission/removal factor tools

Activity data x emissions/removals factor methods, typically referred to as Tier 1 and Tier 2 methods, are generally easy to implement and communicate. Emissions/removals factor based systems are challenged where there are multiple changes in land use over time. The soil carbon equation in the 2006GL(73) addresses this issue for soils and could be applied for other pools as needed. The degree of the challenge depends on the Approach applied, with Approach 2 creating a greater challenge due to the inability to track multiple changes.

By default, the IPCC guidelines assume a 20-year transition period, but if subsequent land-use changes occur within this period, the emissions/removals factor based systems typically do not have appropriate emissions/removals factors to accommodate multiple transitions and it can be costly to generate the number of factors required. Adopting this linearised 20-year transition introduces bias into the estimates, which needs to be quantified.

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 also to estimate the removal and subsequent future emissions during repeated cycles of clearing and regrowth. This can be done by either tracking the changes through time or by developing a manageable number of statistically representative strata to represent these land uses. Representing such patterns of clearing and regrowth 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). The choice will depend on the policy and reporting needs of the country.

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.

Three main tools have been developed around the activity data x emissions/removals factor method These tools typically support Tier 1, and in some cases, Tier 2 methods: **EXACT**, **ALU** and **IPCC tools**. The IPCC and ALU tools have become widely used and are being continually updated to ensure consistency with good practice. Both generate outputs that meet the requirements of the 2006GL. Tabulated activity data generated from remotely sensed observations can be entered into all these tools. The ALU tool (**Box 18**) is also capable of using GIS data to develop spatially-explicit Approach 2 estimates of emissions, but is not able to support pixel or stand-based approaches over large areas and cannot easily track multiple changes in land use on a single land unit (Approach 3). These tools apply propagation of error techniques to estimate inventory uncertainty.

Box 18: 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 emissions/removals factors and completion of the calculations. The software also has internal checks to ensure data integrity. Since many governments have an interest in mitigating greenhouse gas emissions from agriculture and forestry, and given

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(73) See **Volume 4, Chapter 2, Box 2.1, Formulation B of Equation 2.25, in the 2019 Refinement** (IPCC, 2019).

that 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 carbon stocks, soil carbon 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:

1. Version 5.0 based on the methods in the 2006GL.
2. Version 4.5 based on the methods in the revised 96GL and refined in the 2000 and GPG2003.

The software has several features including the following:

- It accommodates Tier 1 and 2 methods as defined by the IPCC.
- It allows compilers to integrate GIS spatial data along with national statistics on agriculture and forestry.
- It is designed to produce a consistent and complete representation of land use for inventory assessment.
- It allows an enhanced characterisation for livestock.
- It has explicit quality control and quality assurance steps.
- It provides a long-term archive of data and results in digital format.
- It generates emission reports that can be included in communications with interested parties.

2.4.2 Fully integrated frameworks

Fully integrated frameworks 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 emissions/removals factor methods, but can have significant advantages including:

- more efficient integration of remotely sensed data with emissions/removals estimation equations;
- a greater ability to analyse the effects of management on emissions/removals;
- the ability to project emissions/removals estimates to enable scenario analyses;
- the 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 help 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 and can more easily accommodate scenarios with multiple changes on the same piece of land.

Fully integrated Tier 3 frameworks utilise mass-balance models that capture all major carbon pools and movements between them (**Box 19**). 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 (e.g. 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, 2016; IPCC, 2003;(74) IPCC, 2006;(75) 2013 KP Supplement(76)).

Fully integrated Tier 3 methods can also use remotely sensed data 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. As such, these frameworks typically apply Monte Carlo simulations to estimate uncertainty of the estimates so as to handle the increased complexity.

They can provide an efficient processing platform to deal 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

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(74) See **Appendix 3.a.1** of GPG2003.

(75) See **Volume 4, Chapter 12** of 2006GL.

(76) See **2013 KP Supplement, Section 2.8**.

significant advantages over simpler tools including the ability to:

- represent accurately key flows of carbon (e.g. growth and decay from natural processes, harvesting, fire and insect disturbance);
- 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 net 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 and Richards, 2008). The methodological choice depends on the availability of existing data (e.g. remotely sensed, mapping or national forest inventories), required outputs and cost.

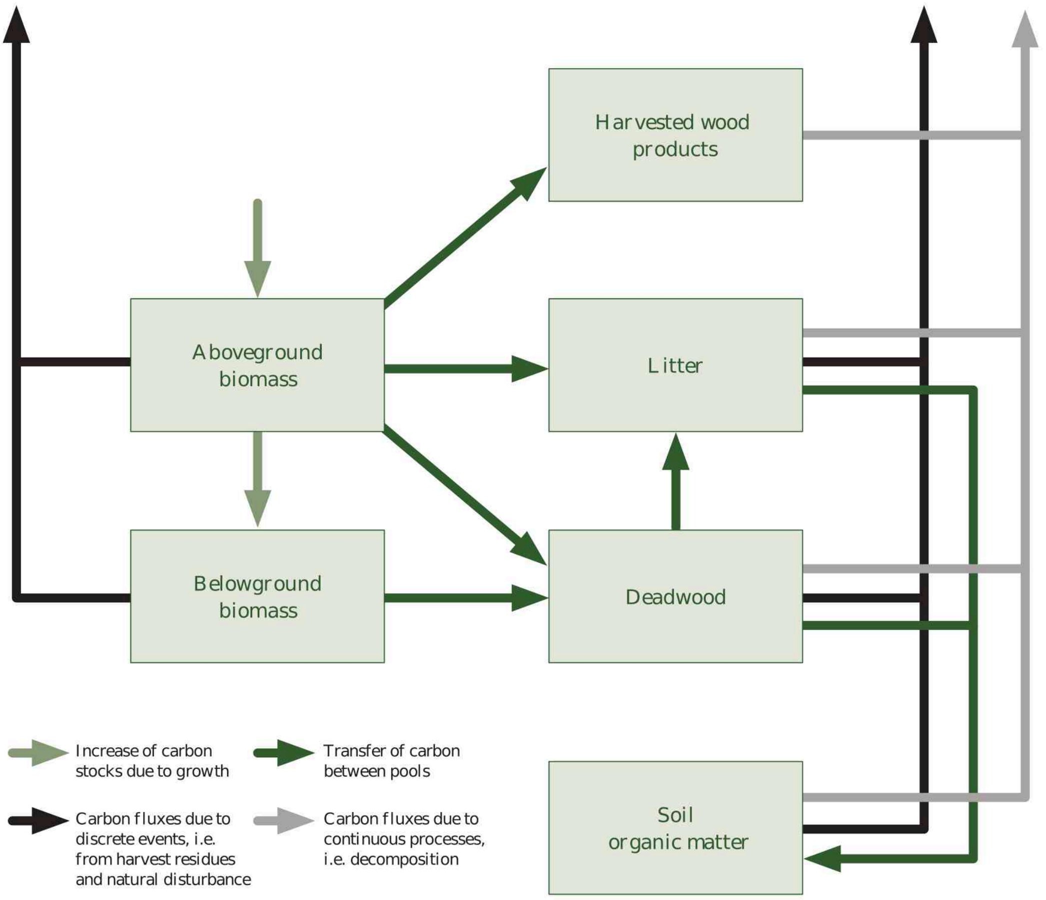
Box 19: Mass balance approaches

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 **Figure 6**. 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 to:

- be able to represent accurately key flows of carbon (e.g. flows from natural processes such as 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 (i.e. flows) that match the net carbon stock change;
- be able to estimate and report uncertainty

Figure 6: Generalised carbon cycle of terrestrial AFOLU ecosystems showing the flows of carbon into and out of the system as well as between the five carbon pools within the system



Source: From IPCC 2006GL Figure 2.1. An additional arrow from the deadwood pool to harvested wood product pool would represent salvage logging operations.

Box 20: Description of examples of fully integrated tools

Several countries utilise fully integrated tools for estimating emissions from Forest Lands. 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). Both have been used to develop multiple inventories in their respective countries and have also been applied in other countries. For example, the CBM-CFS3 has been applied by the Joint Research Centre of the European Union to 26 European 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 up by 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 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).

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, China, 26 European Union countries, Korea, Mexico, Russia and other countries. 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 and Richards, 2008). Analysis and reporting include 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 Australia-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 Australia-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 developed through collaboration between Australia, Canada and Kenya. The need for FLINT arose as there were no existing integration tools that could meet all the requirements of the Systems for Land-based Emissions in Kenya (SLEEK). Due to the cost of developing an integration tool, it was decided to design FLINT as a generic framework to allow other countries to easily adapt the tool to their situation without the development cost. FLINT has been designed as a framework for operational land sector MRV greenhouse gas estimation. The framework is an operational implementation of the AFOLU methods (Tiers and Approaches) provided in the 2006 IPCC Guidelines and is designed to be consistent with the MGD.

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

- Full-mass balance framework that can meet all IPCC requirements.
- A customisable platform to meet national policy and reporting requirements.
- Modular system design that allows countries to easily add their own carbon modules.
- Ability to run in spatially-explicit and spatially-referenced modes.
- Ability to produce reports of past emissions and removals, as well as projections in support of policy analyses, such as REDD+ or mitigation scenarios.
- 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.
- Access to global data sets such as remotely sensed time series data and climate data layers which can be used to augment regional and national data.
- Flexible methods of representing all land uses.

Demonstrations of the FLINT have been undertaken in Colombia, Indonesia, Kenya, Papua New Guinea, Philippines, South Korea and Tanzania has also been extensively tested in Canada as a replication of the CBM-CFS3 model. Each implementation of FLINT in a country is unique to some extent, even though many elements of the framework will be shared. The FLINT development plan includes an independent technical assessment of the framework consistent with a UNFCCC review process for quality assurance purposes.

2.4.2.1 Spatially-explicit methods

Spatially-explicit methods 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 methods.

Three methods are relevant:

- **Stand level methods -** are similar to the methods applied by many forestry agencies to assess timber growing stock. In this configuration, emissions and removals estimates are developed for each stand and the results summed for the entire forest area. Stand-level methods 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 remotely sensed data, but remotely sensed data 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 methods -** track individual pixels as land units, rather than stands, although pixels with similar attributes can be combined to increase efficiencies. Pixel-based methods aim to utilise the full strength of historical time series remotely sensed observations and are suited to situations of multiple changes in land use or cover through time (e.g. shifting agriculture). They are also suited to deforestation and where there is little or no recorded history of forestry activities that could be applied in stand-based methods. Pixel-based methods utilise both spatial and non-spatial data to parameterise the method for each pixel. This is achieved by integration of remotely sensed data with other spatial data sets (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.

2.4.2.2 Spatially-referenced methods

Spatially-referenced methods use information about land use and activities within geographic boundaries. The complete 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, of either remotely sensed data or forest inventory data, 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 suitable for developing projections when the exact location of change is not required. Such methods are applicable for situations where activity data is generated from sampling remotely sensed data and applied to the appropriate models to generate emissions and removals estimates.

2.4.3 Practical considerations in choosing an integration tool

Developing an integration tool, even for the simpler activity data x emissions/removals factor method, requires significant technical expertise and investment of time and money. Integration tools enable synthesising of large data sets into a coherent form and the generation of automated reports. They must be sufficiently transparent for reviewers to understand and evaluate them. 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. Additionally, changing frameworks can be a costly and time consuming task, so choosing the right one is a key **technical design decision** for the NFMS. For this reason, countries may opt to use existing tools rather than develop their own.

Selecting an integration framework for MRV requires consideration of both 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, such as the IPCC principles of transparency, accuracy, consistency, comparability and completeness (TACCC);
- availability of integration frameworks (also referred to as integration tools) and the expertise to implement these within the country;
- cost effectiveness;

Some aspects to consider in making this decision include:

- **Long-term sustainability of the tool -** MRV needs to operate into the foreseeable future and an integration tool should therefore 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 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 remotely sensed 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:

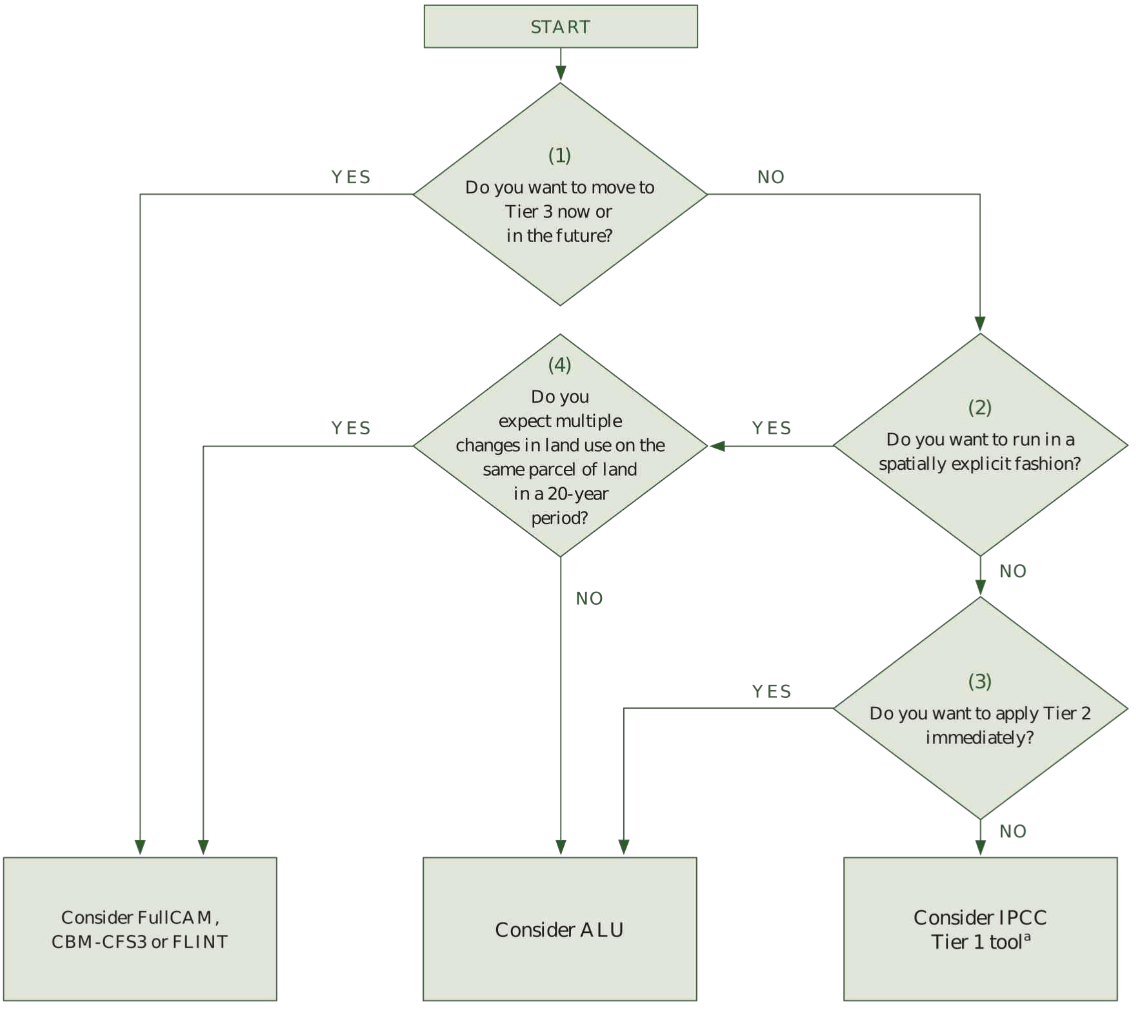
1. **Use an existing tool -** Existing tools cover the full range of Tiers and Approaches and will fit most country circumstances. Each tool has advantages and disadvantages that need to be carefully assessed prior to making any choice (**Figure 7**). These existing integration tools are largely generic 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, dead organic matter 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, 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 the 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 7: 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 for 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 remotely sensed data 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 combine 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 and partially Tier 2, although work is ongoing to allow for a complete Tier 2 capacity.

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

> Remotely sensed observations may reveal many areas that have had multiple land-use changes over short periods. Estimating emission on lands where there have been multiple land-use changes is challenging when using Tier 1 or 2 methods, especially where lagged effects are important (e.g. in the case of soil emissions). The 2019 Refinement addresses the issue associated with multiple changes using Formulation B of Equation 2.25.(77)

2.5 REDD+ methodological considerations

This chapter systematically describes estimation methods for REDD+ activities in a 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.

2.5.1 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 remotely sensed 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. Methods for processing remotely sensed data 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 method 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 (i.e. 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 advice presented in **Chapter 3** and **Chapter 4**, 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 periods could be used.

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 the **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

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(77) See **Volume 4, Chapter 2, Box 2.1 in the 2019 Refinement** (IPCC, 2019).

interventions on land continuing to be used as forests in IPCC terms, forest land remaining forest land. 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 the IPCC, is described in the following sections. **Box 12** summarises how REDD+ activities and IPCC land-use categories relate to each other.

Where NFIs or other design-based sampling methods (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. These carbon stocks can then be applied in the **generation of emissions factors**. Where model-based inferential methods are used, carbon densities for the areas in question are inferred from the model being used and the change in carbon density is modelled. Model-based inferential methods assume that NFI data, where they exist, will be used in the calibration and validation of the models rather than extended to estimate REDD+ activities directly.

It is most likely that countries will use medium resolution optical data to implement MGD advice. Other types of data, including fine resolution optical data and radar, are likely to be used increasingly as availability improves and processing techniques are further developed.(78) Advice on methods based on transitions and trends between strata and within strata is included in **Section 2.4**.

2.5.1.1 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.(79)

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 the 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** and can be used in conjunction with the following advice to estimate emissions

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(78) There is no generally agreed definition of the terms coarse, medium and fine (also called high) 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 remotely sensed data available via the **Space Data Co-ordination Group core data streams**. Intermediate resolutions between 80 and 250 would by default be categorised as coarse.

(79) See **Section 2.2.1, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.**

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 the GPG2003, or where applicable the 2006GL.

Even if the i^{th} conversion did not occur in the current year, there may be emissions arising from the delayed effects (e.g. in the soil carbon pool)(80) for 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-years after the conversion occurred. Therefore it would be reasonable to base deforestation emissions on conversion data covering the past 20-years unless a country does not yet have the tracking capacity required, or wishes to use a longer period, (e.g. to capture ongoing emissions from drained organic soils), or wishes to reassign land to various REDD+ activities, probably for methodological or policy rationalisation. In all cases, countries should ensure that the REDD+ emissions 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, deforestation emissions can still be estimated, but they will show a transient effect as the estimated lagged emissions accumulate. Not accounting for these lagged emissions may lead to bias in the FREL/FRL and emissions reporting. Where the forests are stratified, for example according to the Forest Resources Assessment (FAO and JRC, 2012) into primary forest,(81) modified natural forest(82) and planted forest(83) (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 another time period being used. The IPCC methods identified in **Table 9** 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

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(80) Lagged effects are considered in the **soil organic carbon pool** at Tier 1. Higher Tiers may consider the dynamics of other pools explicitly.

(81) Essentially intact natural forest.

(82) 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.

(83) Forests composed of trees established through planting or seeding by human intervention. They include semi-natural plantation forests with indigenous species and plantation forests comprising exotic species.

of the term significant in the REDD+ context is provided in **Section 2.3.9**.

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

Index i	**Potential conversion**	**Section of the GPG2003 where estimation method is found**	**Corresponding section in the 2006GL**	**2013 Wetlands Supplement**
1	Forest to Cropland	**3.3.2**	**Volume 4, Section 5.3**	**Chapter 5 of the 2013 IPCC Wetlands Supplement. Chapter 2 of the 2013 IPCC Wetlands Supplement**
2	Forest to Grassland	**3.4.2**	**Volume 4, Section 6.3**	
3	Forest to Wetlands	**3.5.2**	**Volume 4, Chapter 7**	**Chapter 3 of the 2013 IPCC Wetlands Supplement**
4	Forest to Settlements	**3.6.2**	**Volume 4, Section 8.3**	
5	Forest to Other Land	**3.7.2**	**Volume 4, Section 9.3**	

Conversion to another land category may be associated with a change in biomass stocks (e.g. part of the biomass may be withdrawn through land clearing), restocking or other human-induced activities. These initial changes in carbon stocks in biomass ($\Delta C_{CONVERSION}$) are calculated as follows:(84)

Equation 1

$$\Delta C_{CONVERSION} = \sum_i ((B_{AFTER_i} - B_{BEFORE_i}) \times \Delta A_{TO-OTHER_i}) \times CF$$

Where:

$\Delta C_{CONVERSION}$ = initial change in biomass carbon stocks on land converted to another land category, tonnes C/yr

B_{AFTER_i} = biomass stocks on land type i immediately after the conversion, tonnes d.m./ha

B_{BEFORE_i} = biomass stocks on land type i before the conversion, tonnes d.m./ha

$\Delta A_{TO-OTHER_i}$ = area of land use i converted to another land-use category in a certain year, ha/yr

CF = carbon fraction of dry matter, tonne C/tonnes d.m.

i = type of land use converted to another land-use category

Note that the carbon factor (CF) may not need to be applied if the estimates of B_{AFTER_i} and B_{BEFORE_i} are given in units of tonnes of C/ha (see **Box 21**).

The calculation of $\Delta C_{CONVERSION}$ may be applied separately to estimate carbon stocks occurring on specific types of land (e.g. ecosystems, site types, etc.) before the conversion. The $\Delta A_{TO-OTHER_i}$ refers to a particular inventory year for which the calculations are made, but the land affected by conversion should remain in the conversion category for 20-years or other period used in the inventory. Inventories using higher Tier methods can define a disturbance matrix for land-use conversion to quantify the proportion of each carbon pool before conversion that is transferred to other pools, emitted

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(84) This appears in the IPCC calculations for each potential conversion type as the quantity B_{BEFORE}; see **Equation 2.16; Volume 4, Chapter 2 of 2006GL.**

to the atmosphere (e.g. slash burning), or otherwise removed during harvest or land clearing.

Advice on estimating the areas converted (which are the activity data required) and on estimating biomass on the Forest Land prior to conversion is provided in **Section 4.2** and **Section 4.3**, respectively. Methods of integration are presented in **Chapter 5**.

In applying the IPCC methods for deforestation activities listed in **Table 9**, the 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 stratification may be used, but should enable reporting of these three forest categories to address the agreed safeguards.(85) These categories also maintain consistency with the FAO Forest Resource Assessment. Modified natural forest(86) may be distinguished by coupe and concession records as well as signs of canopy disturbance, detected using remotely sensed data showing a shift in spectral reflectance (Margono *et al.*, 2012; Zhuravleva *et al.*, 2013), 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 areas or concessions, which should be available via the NFMS from plantation companies or local or national authorities, or by using remotely sensed data. Sub-stratification can be applied 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 significantly reduce variation in biomass density within a stratum.

2. Obtain average biomass carbon stock per unit area for each sub-stratum identified at Step 1:
    a. For primary forest and modified natural forest the biomass stocks per unit area are referred to as B_{PF}, and B_{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 A**). 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 remotely sensed 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, 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.(87)

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(85) REDD+ actions should not be used for conversion of natural forest. See **paragraph 2(e) of Appendix 1 to the Cancun Agreements contained in decision 1/CP.16**. Therefore, tracking of these three forest types will enable demonstration of any conversion of natural forest to plantation. The annual area converted can be calculated as the sum $\sum_{i = 1, 5} A_{(1, i)}$ 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 application of the IPCC methods to these transferred areas.

(86) Modified natural forest may be termed secondary forest in many countries.

(87) Most countries that have a National Forest Monitoring System or NFI are already estimating biomass directly rather than via merchantable volume. The 2006GL includes methods for using both expansion

   b. For planted forest, identified at Step 1 the biomass stocks per unit area can be referred to as the B_{PlantF}, and should be sub-stratified as necessary. B_{PlantF} will depend on the age-class structure of existing planted forests and the 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** use successively as B_{BEFORE} referred to by the IPCC, the average values B_{PF}, B_{MNF} and B_{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 (Sampling), and information available from the NFMS, to estimate the area converted from sub-stratified forest type j to another land use i.

   a. A land-use change is determined by applying national forest definition thresholds and descriptions in combination with remotely sensed 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).

   b. 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 referenced in **Table 9**. 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 biomass density estimated as the difference between the biomass density before conversion and the biomass density for the new land use after conversion. These are called

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factors to convert merchantable volume to biomass, and also using direct measurements to estimate biomass from allometric models. NFIs may also 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. 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.

B_{BEFORE} and B_{AFTER} by the IPCC. Default B_{AFTER} values are available in the 2003GL.(88) A worked example is provided in **Box 21**.

Box 21: Worked example of Tier 1 accounting for deforestation emissions from conversion of Primary Forest to Cropland

A country in a dry tropical climate has experienced a land-use conversion from Primary Forest to Cropland of 7 000 ha. The estimated biomass density of the Primary Forest (B_{PF}) from national data was 174 td.m/ha. The root-shoot ratio of 0.440 was sourced from **Volume 4, Chapter 4, Table 4.4, in the 2019 Refinement** and the subsequent estimate of total biomass was 250.60 td.m/ha. Multiplying this estimate by the carbon fraction of 0.47 leads to an estimate of 117.8 t C/ha. This is known as C_{BEFORE}. The default carbon stocks present on land converted to cropland in the year following conversion was sourced from **2006GL; Volume 4; Chapter5; Table 5.9.** It was $C_{CROPLAND} = 1.8tC/ha$. This is known as C_{AFTER}. The carbon density change as a result of the land use conversion from forest land to cropland was therefore $117.8 - 1.8 = 116tC/ha$. A a total of 7000 ha was converted from Primary Forest to Cropland. This resulted in emission of $116tC/ha \times 7000ha = 812\ 000\ t\ C\ or\ 2\ 977\ 000\ tCO_2e$; which results from the multiplication of molecular weight conversion of C to CO_2 e (i.e. 44/12).

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(88) Refer to the respective sections of the GPG2003 listed in Table 9 for default carbon density in biomass immediately after conversion (B_{AFTER}; tC/ha) for the post deforestation land use. Some factors are given as biomass (t d.m/ha) and others as carbon t C/ha. Multiply values by a carbon fraction (CF) 0.5 to convert dry matter to carbon.

2.5.1.2 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(89) of carbon without land-use change; otherwise there would be deforestation. Since sustainable management may take other forest values(90) 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 in **Section 2.5.1.3**. Degradation may occur in any of the forest types considered. In terms of the stratification suggested by the FAO Forest Resource Assessment 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 percent of deforestation emissions (Houghton *et al.*, 2009) and other estimates have been made at 25 and 47 percent 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;(91)
- 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 the GPG2003.**(92) Detecting forest degradation and then estimating the resulting net GHG emissions requires reliable forest observation techniques, data and resources. Countries should build on 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

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(89) 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.

(90) For example, biodiversity, fire control, water management or productive capacity.

(91) See **Section 2.3.7** for carbon pool definitions.

(92) Corresponding to **Volume 4, Section 4.2 of the 2006GL**.

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 remotely sensed data 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 modified natural forest (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 substrata, and within the strata and substrata affected by human activity (i.e. MNF and PlantF). For estimating degradation, the steps are:

1. See Step 1 in **Section 2.5.1.1**.
2. See Step 2 in **Section 2.5.1.1**.
3. Estimate the annual change in $\mathrm{CB}_{\mathrm{MNF}}$. Call this quantity $\mathrm{B}_{\mathrm{MNF}}$. 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 substratification and factors including forest growth, logging, fuelwood harvest and fire. $\Delta\mathrm{CB}_{\mathrm{MNF}}$ will be positive if $\Delta\mathrm{CB}_{\mathrm{MNF}}$ is increasing, and zero or negative otherwise. In order to ensure that the terms in **Equation 2** have the correct sign, set factor $\mathrm{f}_{\mathrm{MNF}} = 0$ if $\Delta\mathrm{CB}_{\mathrm{MNF}}$ is positive or zero and $\mathrm{f}_{\mathrm{MNF}} = +1$ if $\Delta\mathrm{CB}_{\mathrm{MNF}}$ 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 $\mathrm{LRCB}_{\mathrm{PlantF}}$ and the annual change $\Delta\mathrm{LRCB}_{\mathrm{PlantF}}$. First estimate $\mathrm{LRCB}_{\mathrm{PlantF}}$ 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 22** gives an example of the type of calculations required. Subtract from the current value the value of $\mathrm{LRCB}_{\mathrm{PlantF}}$ in the previous year to obtain $\Delta\mathrm{LRCB}_{\mathrm{PlantF}}$. This will be positive if $\mathrm{LRCB}_{\mathrm{PlantF}}$ is increasing, and zero or negative otherwise. Set $\mathrm{f}_{\mathrm{PlantF}} = 0$ if $\Delta\mathrm{LRCB}_{\mathrm{PlantF}}$ is positive or zero and $\mathrm{f}_{\mathrm{PlantF}} = +1$ if $\Delta\mathrm{LRCB}_{\mathrm{PlantF}}$ is negative.

5. Use the methods described in **Section 4.2** to estimate the annual transfer of areas from primary forest to modified natural forest. Call this quantity $\Delta A_{PF > MNF}$.
6. Use the methods described in **Section 4.2** to estimate the annual transfer of areas from primary forest to planted forest. Denote this quantity $\Delta A_{PF > PlantF}$.
7. Use the methods described in **Section 4.2** 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 **Equation 2**. The significance of the individual terms is described in the steps above and summarised in **Table 10**:

Equation 2

$$\begin{aligned} CO_{2degrad} = \frac{44}{12}(&\Delta A_{PF>MNF} \times (CB_{PF} - CB_{MNF}) \\ &+ \Delta A_{MNF>PlantF} \times (CB_{MNF} - LRCB_{PlantF}) \\ &+ \Delta A_{PF>PlantF} \times (CB_{PF} - LRCB_{PlantF}) \\ &+ f_{MNF} \times A_{MNF} \times |CB_{MNF}| \\ &+ f_{PlantF} \times A_{PlantF} \times |\Delta LRCB_{PlantF}|) \end{aligned}$$

Table 10: Degradation equation terms

Number of terms in RHS of Equation 2	Degradation 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 forest	$\Delta A_{PF > MNF} \times (CB_{PF} - CB_{MNF})$
2	Conversion of modified natural forest to planted forest	$\Delta A_{MNF > PlantF} \times (CB_{MNF} - LRCB_{PlantF})$
3	Conversion of primary forest to planted forest	$\Delta A_{PF > PlantF} \times (CB_{PF} - LRCB_{PlantF})$
4	Decrease in long-term carbon density of modified natural forest	$f_{MNF} \times A_{MNF} \times \|CB_{MNF}\|$
5	Decrease in long-term carbon density of planted forest	$f_{PlantF} \times A_{PlantF} \times \|\Delta LRCB_{PlantF}\|$

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 **Equation 2** 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 that 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 2** should be removed, and treated separately. The terms in **Equation 2** should be subdivided to take account of sub-stratification.

At Tier 1, the 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 emissions/removals factors reported in the IPCC guidance and guidelines for organic soils under different circumstances are summarised in **Table 11**.

Table 11: Sources of emissions/removals 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 emissions factor for cultivated organic soils
GPG 2003	Chapter 3, section 3.4 – Grassland	**Table 3.4.6**	Annual CO_2-C emissions factor for managed grassland organic soils
2006 GL	Chapter 4 – Forest Land	**Table 4.6**	Annual CO_2-C and N_2O-N emissions/removals factors for drained organic soils in managed forests
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 emissions/ removals factors for drained grassland organic soils
2013 IPCC Wetlands Supplement[a]	Chapter 2	**Table 2.1 Table 2.2**	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
2013 IPCC Wetlands Supplement[a]	Chapter 2	**Table 2.3 Table 2.4**	Annual N_2O-N emissions factor for drained organic soils in forest land
2013 IPCC Wetlands Supplement[a]	Chapter 2	**Table 2.7**	CO_2-C and CH_4 emissions/ removals factors for peat fires in all land-use categories

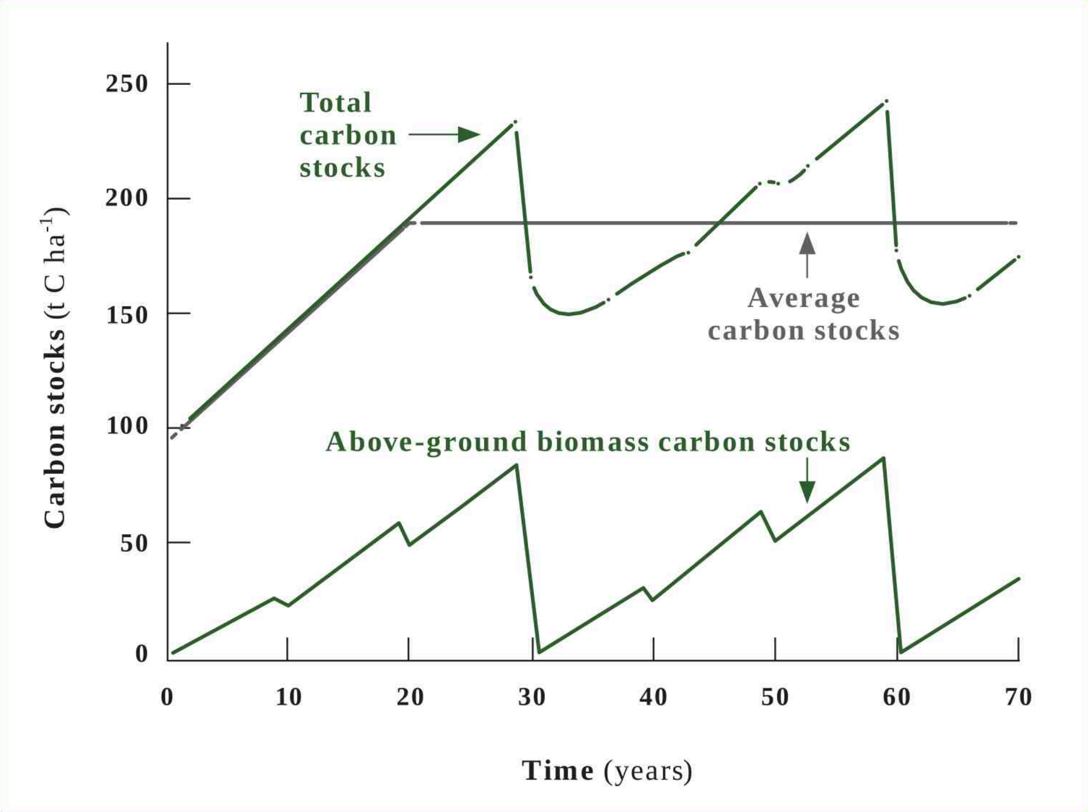
a. There were no updates to these tables in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

b. 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 of filling 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 22: Estimating long-term average carbon stocks in planted forests

Carbon stock (above- and belowground) in a planted forest subject to multiple harvest and subsequent growth will show the saw-tooth pattern illustrated in **Figure 8**. 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 $BD(f_1(t_1/(t_1 + \delta t)) + r)$, where BD is the above-ground biomass density at the time of harvest and *r* is the root-to-shoot ratio. BD 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.

Figure 8: Carbon stock profile over time in planted forest subject to multiple harvest and subsequent growth



2.5.1.3 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 the need for appropriate substratifications. Recognising that countries will have national forest definitions, there seems wide agreement that sustainable management of forests aims to maintain and enhance forest values(93). This does not necessarily mean maintaining the carbon stocks initially present 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 the GPG2003**(94). These methods address above- and belowground 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 remotely sensed 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.

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(93) 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).

(94) Corresponding to **Volume 4, Section 4.2 of the 2006GL**.

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

Equation 3

$$
\begin{aligned}
CO_{2sust} = \frac{44}{12}(&\Delta A_{PF>MNF} \times (CB_{PF} - CB_{MNF}) \\
&+ \Delta A_{MNF>PlantF} \times (CB_{MNF} - LRCB_{PlantF}) \\
&+ \Delta A_{PF>PlantF} \times (CB_{PF} - LRCB_{PlantF}) \\
&- A_{MNF} \times \Delta CB_{MNF} \\
&- A_{PlantF} \times \Delta LRCB_{PlantF})
\end{aligned}
$$

This version of the **Equation 3** assumes that all the forest remaining forest is subject to the REDD+ activity described as either 'sustainable management of forests, enhancement of forest carbon stocks (within an existing forest), and/or conservation of forest carbon stocks; and all terms contribute to the total, irrespective of sign. **Equation 3** is arranged so that CO_{2sust} will be negative (corresponding to a removal) if carbon stocks are increasing. **Equation 3** 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** shows the processes to which the five terms on the right hand side of **Equation 3** 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. 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.

Table 12: Sustainable management of forests equation terms

Number of term on RHS of Equation 3	Process	Term on the right-hand side of Equation 3
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	$\Delta A_{PF > MNF} \times (CB_{PF} - CB_{MNF}$
2	Conversion of modified natural forest to planted forest	$\Delta A_{MNF > PlantF} \times (CB_{MNF} - LRCB_{PlantF}$
4	Conversion of primary forest to planted forest	$\Delta A_{PF > PlantF} \times (CB_{PF} - LRCB_{PlantF}$
5	Change in long-term carbon density of modified natural forest	$A_{MNF} \times \Delta CB_{MNF}$
6	Change in long-term carbon density of planted forest	$A_{PlantF} \times \Delta LRCB_{PlantF}$

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 2** and the sustainable activities then estimated as the difference between **Equation 2** and **Equation 3**. If **Equation 2** has been disaggregated in some way (e.g. by treating planted forests separately), then **Equation 3** should be disaggregated in the same way.

- If all degradation and the sustainable activities are to be estimated together only **Equation 3** should be applied. Since there are no sign restrictions in **Equation 3** 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, the 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 3** 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 the GPG2003**. Tier 1 carbon dioxide emissions/removals factors reported in the IPCC guidance and guidelines for organic soils under different circumstances are summarised in **Table 12**.

2.5.1.4 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 22**. 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 2.5.1.2**). 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(95) 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,(96) 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 the GPG2003**, Land Converted to Forest Land, corresponding to **Volume 4, Section 4.3 of the 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. Remotely sensed data may not always be a useful 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

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(95) See **Section 1 of the GPG2003** for a discussion of forest definitions including managed and unmanaged forest.

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

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 Step 1. This will improve the accuracy of results.
3. Utilise 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 the 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.
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.

2.5.2 Forest Reference Emission Levels

An NFMS is likely to need to consider methodological issues associated with the construction of FREL/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.(97) Other useful sources of information related to FREL/FRLs include:

- **the GOFC-GOLD Sourcebook**;
- **UN-REDD's Emerging approaches to Forest Reference Emission Levels and/or Forest Reference Levels for REDD+**;
- **the Technical considerations for FREL and/or FRL construction for REDD+ under the UNFCCC**; and
- **the World Bank Carbon Fund Methodological Framework**.(98)

2.5.2.1 Consistency with the Greenhouse Gas Inventory

Countries should ensure consistency between FRELs and/or FRLs, REDD+ emissions and removals estimates and GHGIs.(99) Consistency does not necessarily imply that the coverage of pools and gases

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(97) This material is based on advice previously published as a GFOI MGD Rapis Response Module, which provides guidance on technical issues related to **decisions 12/CP.17** and **13/CP.19**. It can be downloaded from the **GFOI website**.

(98) 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.

(99) **Paragraph 8 of decision 12/CP.17** says that consistency between the FREL/FRL 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 the FREL/FRL.

is identical.(100) 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 incentivising actions to mitigate GHG emissions associated with REDD+ activities.

If differences exist in the coverage of pools and gases between the FREL/FRL, REDD+ activity estimates and the GHGI, an 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 **Section 2.5**.

Consistency can be enhanced if:

- The definition of forest, including how managed forests are defined, is the same for REDD+ GHG estimates, FREL/FRLs and GHGI.
- REDD+ activities are identifiable in the GHGI as IPCC categories, subcategories, or sums of categories or sub-categories. **Table 13** shows the relationship between REDD+ activities, IPCC categories, and the sections of the MGD that 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,(101) (e.g. due to 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/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**), which includes systems where there is 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. A clear description of what is included in the FREL/FRL is needed and there may be some need for reconciliation between categories used in the GHGI.
- Activity data and emissions/removals 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** (**Volume 4, Chapter 3 of the 2006GL**) with the sum of areas of land uses adding up to the national land area.

Table 13: Relationship between REDD+ activities, IPCC categories and the MGD advice

REDD+	IPCC Land-Use Change Descriptions	MGD Advice
Reducing emissions from deforestation[a]	Forest land converted to other land uses	**Estimation of emissions from deforestation**[b]
Reducing emissions from forest degradation	Forest land remaining forest land	**Estimation of emissions from degradation**

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(100) Consistency is unlikely if the GHGI is old, and if significant REDD+ readiness funds have been used to build a more advanced system for REDD+ MRV. In these cases, initial inconsistency is much preferable than consistency with an outdated GHGI and creates an opportunity to build consistency in future GHGIs. Therefore, GHGI and REDD+ estimates are often inconsistent in an interim period until the GHGI method and approaches are updated, generally following FREL/FRL submission and review.

(101) In the case of deforestation, to summation over inventory categories, namely conversion of forest to other land uses.

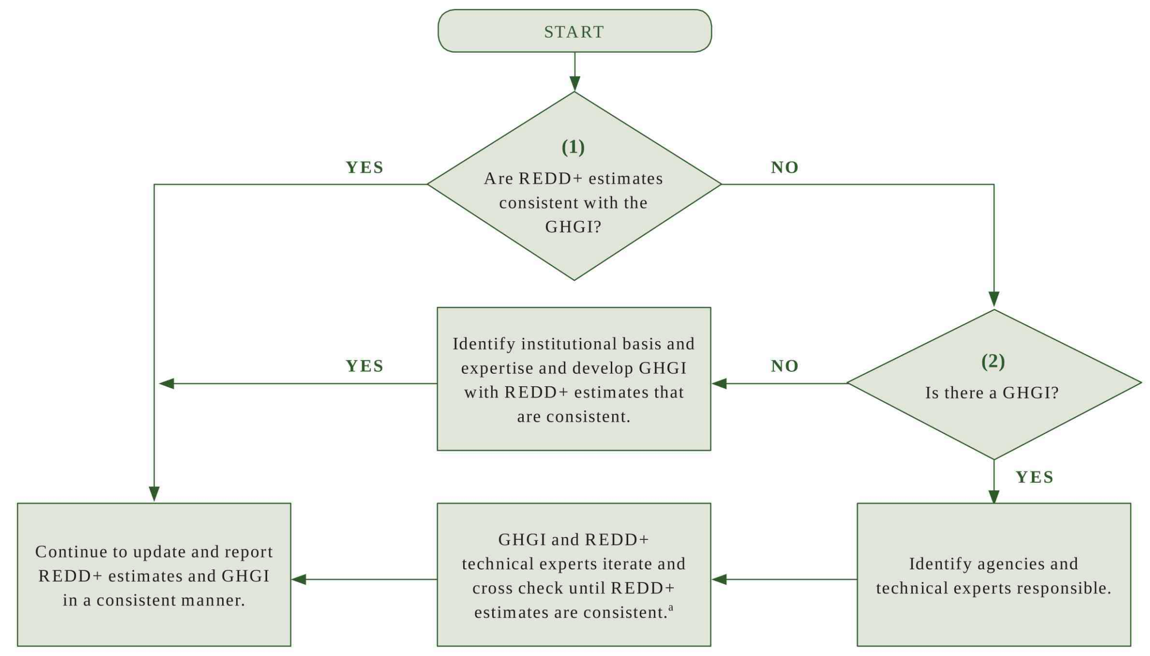
REDD+	IPCC Land-Use Change Descriptions	MGD Advice
Sustainable management of forests	Forest land remaining forest land	**Sustainable management of forests, enhancement of forest carbon stocks (within existing forest) and conservation of forest carbon stocks**
Conservation of forest carbon stocks	Forest land remaining forest land	**Sustainable management of forests, enhancement of forest carbon stocks (within existing forest) and conservation of forest carbon stocks**
Enhancement of forest carbon stocks (within an existing forest)	Forest land remaining forest land	**Sustainable management of forests, enhancement of forest carbon stocks (within existing forest) and conservation of forest carbon stocks**
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	**Enhancement of forest carbon stocks (afforestation of land not previously forest, reforestation of land previously converted from forest to another land use)**

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, 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.

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 9** shows how institutions can interact to achieve consistency.

Figure 9: 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 for 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 subnational 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 as part of their National Communications and Biennial Update Reports.

2.5.2.2 Types of Forest Reference Levels

GHGIs may not be produced every year, but once consistency with the GHGI is established, the historical data used to estimate FREL/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. However, this is only one option and it can have significant limitations under certain circumstances, especially where reforestation or enhancement activities represent a large component of the FREL/FRL. 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, 10 to 15 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 a possible relationship with drivers. A key factor is also the number of estimates during this time. For example, it is not possible to understand trends where only two or three time-points are developed over a 10 to 15 year period.

The Landsat archive provides data from which time series for GHG emissions and removals associated with REDD+ activities can be estimated.(102) Once established, time series can be extended and/or revised as new data become available and the information incorporated into updated FRELs/FRLs. **Table 14** describes some different types of reference levels consistent with COP decisions and **Figure 10** suggests a decision tree for choosing between them. The most appropriate FREL/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 the 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.

Table 14: 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 to 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. Where a trend is present over the historic period (e.g. a decrease or increase in deforestation), a historical average will lead to errors in emissions reductions calculations.
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/FRL than Type 1. Could adopt Type 1 initially, then move to Type 2. This may address some issues of error due to ongoing trends, but not as well as Type 4.
3.Cumulative average 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.	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.

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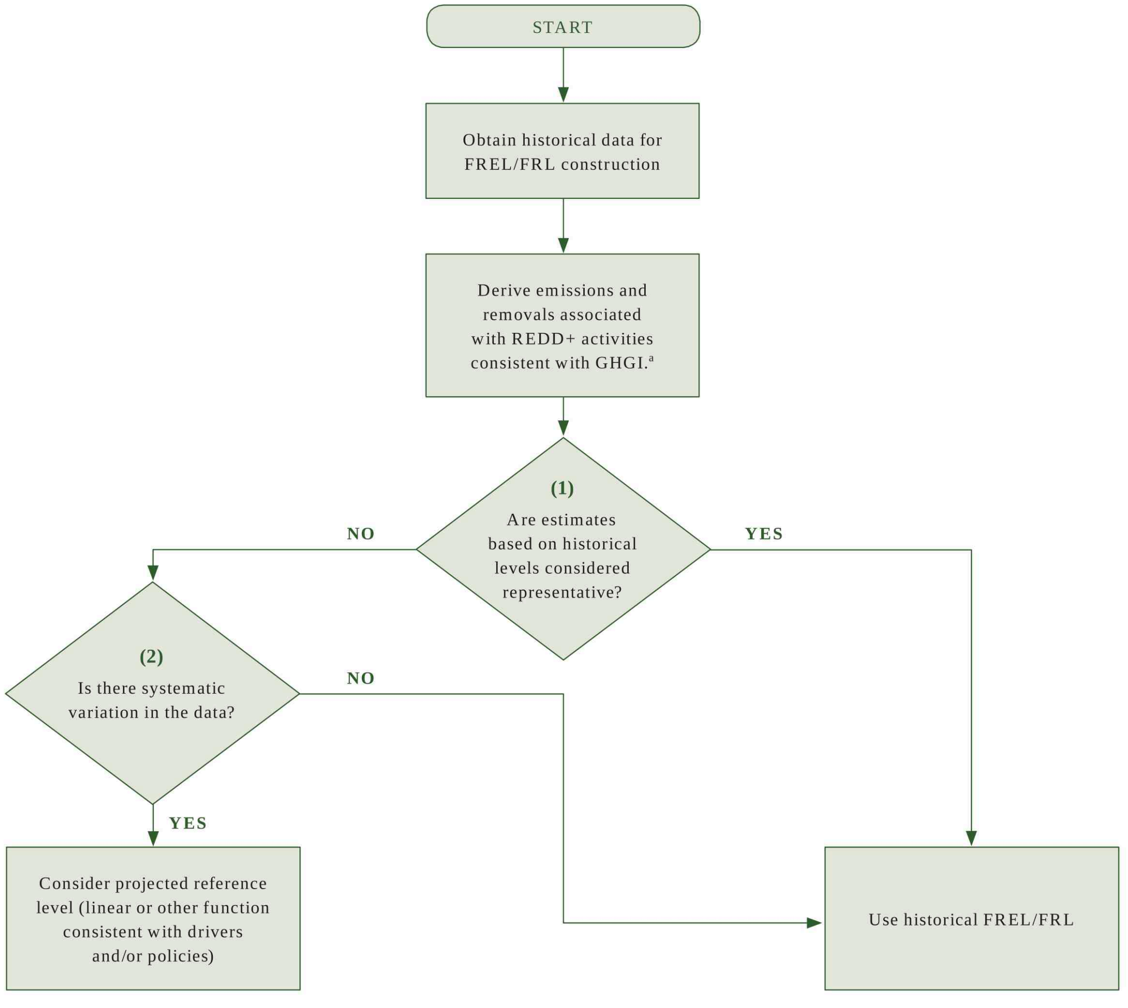
(102) Historical Landsat data are freely available as a core data set and can be accessed via the **United States Geological Survey (USGS) Data Centre**. The continuing work of the GFOI to ensure the long-term availability of space data is detailed on the **GFOI webpage**.

Type of reference level	**Description**	**Notes**	**Possible reasons for choice**
4.Trend extrapolation	Extrapolation of trend fitted to historical data.	Needs strong 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.	This is well suited to circumstances where there is a clear trend in the historical data.

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. Transparency in models is discussed in the report of the **IPCC Expert Meeting on Use of Models and Measurements in GHG Inventories (Sydney 2010)**, possibly including expectations underlying the forest transition curve.	This is well suited where there is a clear trend in historical data with understanding of the causes. It is also useful where there are more complex activities being undertaken (such as changes in forest management practices).

Figure 10: 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 for 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 14**.

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 general 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 14**.
>
> As noted in **Table 14**, there are several methods for calculating FREL/FRLs. While all FREL/FRLs are presented as emissions and/or removals, they can be produced using two distinct methods 1) applying the methods in **Table 14** to the emissions and removals estimates themselves; or 2) when using the gain-loss method, applying the methods in **Table 14** to the activity data, then applying the appropriate EFs or models to calculate the FREL/FRL.

Depending on the estimation methods applied and the activities being estimated, there can be a considerable difference between the two methods. This is particularly the case for newly planted forests that will be harvested. For example, in many countries the plantation estate has expanded rapidly over the past decade. Initially, removals will be large in these areas, but once harvesting of the forest estate starts, removals will drop rapidly, eventually approaching zero unless new areas are planted or management changes. In these circumstances simply averaging emissions/removals will probably lead to the overestimation of removals in the FREL/FRL. The same issue will occur in other activities and land uses where there is recently land-use change that lead to ongoing emissions and removals into the future. This issue can be avoided by using the methods in **Table 14**, but applying them to the area or activity data, then applying emissions estimation methods that include expected management, such as harvesting.

2.5.2.3 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/FRL may be adjusted.(103) The decision tree in **Figure 11** suggests a framework

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(103) Some results based payment frameworks such as the Forest Carbon Partnership Facility, may have specific requirements and restrictions around when adjustments can (or can not) be made.

for assessing when this could be the case.

Figure 11: 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 for 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 have 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/FRL, or by a projected FREL/FRL level (see **Table 14**) 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/FRL based on model simulation projections (**Table 14**; 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/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+.

2.5.2.4 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 an 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). As a result, countries have increasingly included uncertainty analysis in their submissions, including both a qualitative or quantitative evaluation of sources of uncertainty.(104)

Uncertainties in annual emissions or removals associated with REDD+ activities can be estimated using the methods outlined in the MGD, consistent with IPCC Guidance.(105) 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 deforested areas are uncorrelated.

On the other hand, for emissions/removals 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, estimating 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 is described in **Section 4.2.3**, and the calculations for uncertainties in emissions/removals factors, including both the correlated and uncorrelated cases, are described in **Section 4.4.1.2**. This contains a Box 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

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(104) A total of 83 percent of **FREL/FRLs submissions to the UNFCCC** in year 2020 included a discussion or quantification on sources of uncertainty.

(105) **GPG2003 Section 5.1 and 5.2** or **2006GL, Volume 1, Section 3.2.3.1**.

most efficient use of available resources. By identifying these categories, efforts to improve overall estimates can be prioritised.

2.5.2.5 Stepwise approach and updating

Under a stepwise approach,(106) FREL/FRLs (and GHG estimates/inventories) 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, ensuring prioritisation of the most relevant sources and sinks, and in the context of REDD+, activities. Future improvements in data could also involve establishing National Forest Inventories and intensive monitoring sites, for improved forest policies and resource management, and improved reporting capabilities to meet the MRV goals of the NFMS.

Additionally, a stepwise approach as a way to incorporate better data or methodologies is related to the more general requirement for Parties to update FREL/FRLs periodically as appropriate,(107) taking into account new knowledge, new trends and any modification of scope and methodologies.(108) When updating, Parties should maintain methodological consistency between the REDD+ GHG estimates and the FREL/FRLs. This may entail improvements to the GHGI, as well as to the FREL/FRL estimates; the point is that they should be mutually consistent. Parties should also maintain **time series consistency** when submitting the estimates with new data, methodologies, pools or activities, which requires the back calculation of the entire time series when new data/methods are adopted or the MRV scope is expanded.(109)

2.5.2.6 Number of reference levels per Party

Annexes to **decisions 12/CP.17** and **13/CP.19**(110) 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.(111) FRLs also allow for the summation of the activities that can result in both emissions and removals. Summation should avoid double-counting between FRELs and FRLs.

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

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(106) See **paragraph 10 of decision 12/CP.17**.

(107) **Paragraph 15 of decision 12/CP.17** establishes a process for the technical assessment of updated, as well as newly submitted reference levels.

(108) See **paragraph 12 of decision 12/CP.17**.

(109) Refer to **Volume 1, Chapter 5, of the 2019 Refinement**. (IPCC, 2019).

(110) **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.

(111) 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.

FRLs will be accompanied by **technical reassessment**.

2.5.2.7 Subnational Forest Reference Levels and nesting

Subnational FREL/FRLs may be developed as an interim step on the way to development of national FREL /FRLs.(112) In this case, development of the 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 how any subnational monitoring systems will be integrated into a national monitoring system".(113) Integration into national monitoring systems will be easier if the boundaries of subnational activities and hence their associated FREL/FRLs correspond to boundaries in the stratification process of the national GHG inventory, since this will help to deliver consistency between the two.

If the national FREL/FRL already exists as a sum of subnational FREL/FRLs(114) estimates of displaced emissions are not required for international reporting. Where is this not the case, utilisation of remotely sensed data or ground-based observations could assist in establishing whether there is displacement of emissions outside the boundary of the subnational FREL/FRL. 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.

Nesting is both a policy and technical construct. In the context of the UNFCCC, countries are encouraged to initiate REDD+ implementation through national policies. However, many countries have existing forest carbon projects operating at a much smaller level (e.g. at the scale of individual land owner or land manager) which can be successful in contributing to national mitigation goals. In this context, nesting can refer to how governments incentivise local, smaller-scale activities and integrate them with larger national (or subnational) programmes to achieve their NDC and support low-carbon development. REDD+ nesting can be especially critical where responsibility for, and the impacts of, land management are decentralised.

Nesting is also needed when countries apply for results-based finance at both national and subnational levels, or if there are active REDD+ projects within the country's borders. In this context, inconsistencies between the NFMS estimation framework and that of the project can create technical challenges. This is particularly likely where projects have been established under voluntary programs prior to the establishment of the national MRV system (sometimes referred to as legacy projects). In such cases, they are likely to have adopted different methodologies and have included different carbon pools (or even different REDD+ activities) from those adopted at national level. Additional complexities are introduced when trying to maintain consistency with the national (or interim subnational) system, including, but not limited to, boundaries, double counting, leakage and attribution. Moreover, projects and activities may use different definitions, sources of data, data and methods compared with those used for the national system, including different Approaches for land representation and methodological Tiers (IPCC, 2019). These differences, combined with international trading of verified carbon units generated from these projects in the voluntary carbon

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(112) See **paragraph 11, decision 12/CP.17**.

(113) See **paragraph 71(c), footnote 7 of decision 1/CP.16**.

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

market, makes the nesting of these projects within a national system technically challenging.

Early experiences of countries' attempts to address technical challenges associated with nesting (Lee *et al.*, 2018; FAO, 2019) suggest that:

- There is no one-size-fits-all formula to design and implement REDD+ nesting, because it depends on the national circumstances of each particular country.
- Flexibility is needed to transition legacy projects into a national (or subnational) system.
- Counterfactual baselines (e.g. avoided deforestation) make nesting more challenging than where a baseline can be set to zero for non-forestland (e.g. afforestation/reforestation) or forest management (where similar methods can be applied at small and large scales).
- Spatially-explicit information, applicable to nested systems, can help to address both policy and technical challenges.

Box 23: Nested approaches for REDD+ project activities

Reconciling REDD+ activities at project, subnational and national level requires a concerted effort, but when well-designed, a nested system can contribute to national mitigation targets in various, and critical ways.

Nesting local-scale activities can attract private investment, provide lessons that can be replicated at a larger scale, and combine the impacts of multiple mitigation activities being implemented by different stakeholders across the landscape, which is of particular importance where the government lacks resources to roll out REDD+ at scale and wishes to encourage private investment.

While this section focuses on the methodological issues related to nesting, national policy setting and directives have as much, if not more, of a bearing on the approach to nesting as technical issues. Methodological challenges represented by nesting can be summarised within three themes.

Data and methodological mismatches

Data and/or methods used by national administration for reporting GHG inventories to the UNFCCC differ from those used by REDD+ projects. Such differences are typically more significant with legacy projects.(115) Data to measure results may flow top-down or bottom-up (or both). In Brazil, data are flowing from the national system to the states; in Australia, a more sophisticated system integrates data flows in both directions.

Subnational jurisdictions typically use national data and are therefore more easily aligned to national estimates than single projects. On the other hand, the national system can benefit from subnational jurisdictions that collect finer resolution spatial data with a higher temporal frequency and/or region- and/or stratum-specific carbon stocks by integrating those data collection systems into its monitoring system. Spatial and C-stocks data with higher spatial and temporal resolution allow the use of higher reporting approaches and tiers within a higher number of strata, thereby enabling the preparation of estimates with higher levels of accuracy and precision.

For instance, Approach 3 for land representation can be allowed by such enhanced data sets, thereby enabling an estimation of GHG emissions or removals with higher accuracy. Given

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(115) **https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf**

that project activities often include estimates for dead organic matter and soil organic carbon, overall completeness of the national GHG estimates will also be enhanced.

In any case, when using data collected from activities and projects for preparing or evaluating information and estimates reported in the GHGI, estimates must be fully consistent with IPCC good practice. Accordingly, the following steps should be considered:

- Define the spatial boundaries of the territory impacted by the project activity.
- Identify the land-use categories and subcategories of the GHGI impacted by the project activity.
- Define the reference conditions (e.g. climate, soil, management system) of the activity/ project.
- Identify pools and gases impacted by the activity.
- Identify the time frame (temporal boundaries) of the activity and ensure full reporting of any legacy emissions and removals associated with it.
- Define the level of variability (heterogeneity) of the data, and their applicability outside the project boundaries (spatial and temporal).
- Ensure that the data are available and consistently applied for the entire time series.

Reference level setting or allocation

Approaches to setting the reference level and the associated forest monitoring are likely to be affected by the nesting within a National REDD+ reporting supported by a National Forest Monitoring System, since in such a case full consistency with IPCC good practice is ensured, as well as the ever-tracking of results achieved across time within the National GHG Inventory. Further, the different temporal boundaries of a national systems will probably produce different estimates of reference forest-related emissions and removals compared with projects. However, such enhanced estimates address any displacement of emissions within the forest land category, as well as the permanence of reported results provided that the national monitoring system keeps collecting and compiling information to be reported.

Project baselines can be aligned with jurisdictional/national programs by adopting:

- an allocation determined by the government, or otherwise agreeing on an adequately aligned project baseline; and
- other aspects and requirements of the jurisdictional/national program, such as, government approvals, monitoring, leakage, performance, safeguards and benefit sharing plans.

Avoidance of double counting

Nested systems need to avoid any double counting. The stratification of national GHGI categories/subcategories into subdivisions that meet the boundaries of the project activities avoid double counting of emissions and removals from a single category that is impacted by more than a project activity. Further, this avoids emissions and removals from any single unit of land being counted under more than one REDD+ activity, which would otherwise result in a double counting of GHG fluxes and consequently of benefits achieved. Double counting can also be avoided by allocating emission reductions, as in Brazil's new Amazon incentive system, which provides states with a percentage of emission reduction units achieved at the higher scale rather than allowing the issuance of nominal units against baselines at the project scale. This may, however, reduce incentives for sub-units to perform.

In conclusion:

- Methods for estimating carbon stock changes at national level are not always fit for purpose for incentivising action on the ground. Thus, flexibility is needed to transition legacy projects into a national (or subnational) system.
- Nesting of avoided deforestation where counterfactual baselines have been adjusted is challenging.
- Nesting within the NDC makes it possible to ensure that displacement of emissions from project activities is addressed and that the permanence of results is secured.

Source: Elaborated from FAO, 2019; Lee *et al.*, 2018; Sandker, 2018; IPCC, 2019

Chapter 3 Data Sources

Any general discussion of data requires a careful distinction between data sources and data uses. For both the gain-loss and stock-difference methods, the primary data sources are:

1. ground observations and measurements and predictions based on them such as biomass per unit area; and
2. spatial data including remotely sensed data or products predicted from these data. The main data uses are as reference data or as auxiliary data.

Reference data are the data on which estimates are based. For example, emission factors applied in Tier 1 and 2 methods generally require ground plot information in the form of observations of tree species and measurements of diameters and perhaps also tree heights. The actual reference data are then plot-level aggregations of single tree allometric model predictions.

For Tier 3 methods, reference data can be used for model construction and in model calibration (i.e. parameterisation) with such data ideally representative of the population. In practice, this does not mean that all environmental conditions are covered, but that the reference data includes a range of the conditions existing in the country that is representative of national circumstances (IPCC, 2019).(116)

Model calibration is the process of selecting or adjusting model parameters to obtain results that best represent the processes of interest in the region (and time period) for which the model will be applied. The model calibration procedure readies a model for its further use in analyses. There are multiple methods for calibrating models. Simpler empirical models (e.g. empirical forest growth models based on forest age or site indices) are commonly mathematical representations of relationships between carbon stocks or stock changes and relevant predictor variables using standard statistical methods and software. More advanced models (e.g. hybrid or process-based models) typically have numerous, interrelated predictor variables and associated parameters. For hybrid and process-based models calibration is often completed using parameter optimisation methods that vary the model parameters within known ranges to best match known results (e.g. carbon stocks). There are several methods for doing this, including generic algorithms, machine learning and Bayesian. The methods may also be used to propagate uncertainty through the inventory analysis (e.g. Hararuk *et al.*, 2017).

Once the model has been constructed or calibrated, it should be evaluated to demonstrate that it effectively simulates measured trends for the source category of interest. Data independent of those used for model calibration should be used when evaluating model behaviour and to confirm that the model is capable of estimating emissions and removals in the source categories of interest (IPCC, 2019). In practice, this is typically achieved by setting aside a subset of reference data collected and used in model calibration to be used exclusively for model evaluation.

For estimation of activity data, reference data may also be in the form of plot-level ground data, but more frequently reference data for this application are in the form of visual interpretations of aerial photography or satellite imagery. Thus, data from both ground and remotely sensed sources may serve as reference data.

The main purpose of auxiliary data is to enhance or improve estimates based on reference data, with the primary enhancement being increased precision. Examples include the use of a map generated from remotely sensed data as the source of stratification data and the use of spectral and/or airborne laser scanning data integrated with ground data for use with model-assisted or model-based estimators. For tropical greenhouse gas inventories, auxiliary data are most often in the form of remotely sensed

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(116) **See Volume 4, Chapter 2, Section 2.5.2**.

data, or products based on remotely sensed data. However, spatially-explicit climatic, topographic and management data can also be used in support of attribution (i.e. associating observed land cover and cover changes with land use and land-use change). Thus, just as data from ground and remotely sensed sources can serve as reference data, data from both sources can also serve as auxiliary data. This section addresses data sources, with data uses addressed in **Chapter 4** and **Chapter 5**.

3.1 Remotely sensed observations

When assessing the utility of remotely sensed observations to support reporting requirements, consideration of forest definition, temporal and spatial resolution, budget for acquisition and means of processing are highly relevant. The MGD anticipates that medium (10-80 m) and fine (<10 m) spatial resolution optical and radar data will be the main types of remotely sensed data used in estimating REDD+ activities.(117) Currently, there is most experience with using medium resolution optical data. This is partly because many countries have used optical data of this resolution in making national emissions estimates from deforestation and from other LULUCF activities, and because Landsat provides a historical archive of data back to the early 1970s.(118) Given the successful operations of Landsat 8 and Sentinel-2A/2B and long-term plans for their follow-on missions, there is also the prospect of continued availability of data for the foreseeable future. Landsat and Sentinel-2 data are acquired globally and are freely available in pre-processed form. New techniques in data mining or compositing can also do much to mitigate problems of interference by cloud cover.

Radar data now have the potential to play a greater role for national forest monitoring than in the past, with several radar satellite missions, operating at different wavelength bands and spatial resolution, currently in operation. Globally consistent historical L-band radar data from JERS-1 SAR and ALOS PALSAR exist back to the mid-1990s, in C-band the ERS-1/-2 and Envisat missions provide global data sets, however less systematic than the L-band missions. Missions currently in operation such as Sentinel-1A/1B, ALOS-2 PALSAR-2 and SAOCOM-1A/1B(119) all have global systematic observation plans in place. Of importance, the free data policy and global acquisition strategy of Sentinel-1A/1B provide SAR data of high relevance to MRV. There are also good prospects for sustained global radar data availability in the future, with a range of public open radar missions planned well into the next decade. The majority of these are planned to have an open data policy, making them relevant for example in the context of biomass monitoring (Herold *et al.*, 2019). For example, the NASA-ISRO SAR Mission (NISAR) and ESA's Biomass Earth Explorer, both planned for launch in 2022, will be collecting SAR data of great relevance for MRV.

In support of GFOI, the CEOS works with national space agencies and Earth observation data providers to ensure that all countries can have open and free access to the satellite data required for national forest monitoring and annual reporting of greenhouse gas emissions. The CEOS Systems Engineering Office (SEO) produces **online Country Coverage Reports** for the Landsat, Sentinel-1 and Sentinel-2 missions for more than 70 GFOI countries. Relevant to all Earth observation data, there is also a strong movement among CEOS agencies to facilitate access to satellite data in so-called Analysis Ready Data (ARD), which are preprocessed data to reduce the required expert knowledge to ingest and prepare for the analysis. CEOS Analysis-Ready Data for Land (**CARD4L**) represents a set of data format specifications for optical, radar and Light Detection and Ranging (LiDAR) sensors to

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(117) Although remotely sensed observations should always be used in combination with ground data plots for estimation of activity attributes, such as areas or emissions factors, remotely sensed data can provide spatially-explicit measurements over national scales.

(118) Archive images at 30 m resolution are available from 1980s.

(119) At the time of publication SAOCOM-1B has yet to launch.

ensure that ARD products provided by CEOS agencies adhere to a common standardised format. Data products provided in CARD4L format represent satellite data that have been processed to a minimum set of requirements and organized into a form that allows immediate analysis with a minimum of additional user effort and allows interoperability both through time and with other data sets.

3.1.1 Optical data

Optical data are generally considered to be most useful for estimating activity data (both for deforestation and forest degradation), than for emissions factors, which more generally involves the use of **ground-based observations**.

The pixel size of optical data influences its utility, and coarse resolution (generally considered as pixel sizes between 100 m and 1000 m) is generally regarded insufficient resolution for estimating REDD+ activity data. In general, medium resolution (10 to 80 m) data are used for monitoring in this context, and specifically Landsat data at 30 m resolution are commonly used for mapping activity data for monitoring REDD+ activities (**GOFC-GOLD Sourcebook, 2015**). The temporal frequency, coverage, length of the archive, availability of processed images (such as Analysis Ready Data), and free access of data also influence the utility of data. One of the major constraints of optical data is the lack of images in cloudy areas, with parts of the humid tropics experiencing persistent cloudiness. Several optical data sources with an open data policy and long-term service plan are discussed.

Landsat as the most commonly used data type has several advantages including:

- a long history of use;
- global acquisition;
- pre-processing and archiving of data;
- free access to data;
- spectral bands critical to forest monitoring including near and shortwave infrared; and
- long time series of data available for virtually any place on Earth.

Landsat is often the only optical data set available for estimating historical activity data, due to the long record required for time series analysis, and which can be used in the production of baselines and reference levels. It also has a thermal band that helps in the identification of clouds. Historical Landsat coverage is good for most of the tropical forests. The Landsat data series goes back to the 1970s, but consistent analysis-ready Thematic Mapper (TM) images are available from the historic archive dating back to 1984, corresponding with the launch of Landsat 5. With the launch of Landsat 8 in 2013, the time series is expected to continue for the foreseeable future. Construction of Landsat 9 has begun, with an anticipated launch in 2021. The availability of the historical archive is particularly important for establishing reference levels. Similarly, consistent observations over time remain the key to automated methods for detecting deforestation and forest degradation. 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 the number of images being collected and archived.

The Copernicus Sentinel-2 mission, comprising a constellation of two polar-orbiting satellites, has increased, with its swath width of 290 km and 5-days revisit time (at the Equator with two satellites), the availability of medium resolution data. It has 13 spectral bands, 4 visible and near-infrared bands at 10 m, 6 red-edge/shortwave-infrared bands at 20 m, and 3 bands at 60 m spatial resolution, the latter specifically useful for atmospheric corrections and identification of clouds (Zhu *et al.*, 2015). The multispectral instrument provides enhanced continuity to the French SPOT series of satellites and the US Landsat Thematic Mapper instrument, albeit lacking a thermal band. With its free and open data policy, it makes 10 m resolution data available in dense time series, facilitating applications that have hitherto been regarded as only possible at fine resolution. As part of the European Union's Earth Observation Programme, Copernicus Sentinel-2A was launched in June 2015 and Sentinel-2B in March 2017. Each satellite has a design mission lifetime of more than 7-years and fuel for 12-years. Alongside Sentinel-2C and -2D, two additional satellites have been funded and are currently under development to guarantee data continuity. In the future, as the time series increases, Sentinel data are likely to become standard for monitoring REDD+ activities.

Data at spatial resolution finer than 10 m can improve the detection of changes associated with regard to 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 fine resolution data for wall-to-wall mapping for REDD+, including Guyana (**Box 25**), but acquisition and processing costs are greater than for medium resolution data. Also, finer 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, fine resolution optical data have so far been used mainly for collecting reference observations in sample-based approaches to area estimation and 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. Finer 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) to estimate the 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 fine resolution data continues to be the subject of research. However, the planned procurement of fine resolution data by **Norway** may provide an option for more operational use of the data for activity data estimation, as well as for training and validation of results.

Coarse resolution data from sensors such as MODIS, VIIRS, CBERS-2 and OLCI on Sentinel-3 can be useful, for example to derive changes in spectral indices to detect where changes are occurring in forests, for stratification purposes or to guide sampling. High frequency, coarse resolution data also have the benefit of potentially providing data which can augment that of other data sources in cloudy areas.

Box 24: Removing clouds and cloud shadows in optical satellite imagery used for mapping activity data

The opening of the Landsat archive in 2008 (Woodcock *et al.*, 2008) allows time series of Landsat data to 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 (i.e. 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 the Continuous Change Detection and Classification (CCDC) algorithm for mapping activity data (e.g. Arévalo *et al.*, 2020), 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 and Woodcock, 2012). 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 and Woodcock, 2014a). The single image cloud screening algorithm referenced here, Fmask, has been implemented by the USGS to screen all Landsat images in the US archive, such that each image is delivered with an Fmask-based cloud/cloud shadow mask. Fmask and other 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 30**, 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 (e.g. Griffiths *et al.*, 2014).

Box 25: Progressive Development and Adaptation of Guyana's Monitoring, Reporting and Verification System

Guyana has developed an MRV process that provides the basis for reporting performance measures tied to changes in forest cover and forest carbon stocks. The MRV process is supported under the terms of the Joint Concept Note which Guyana and Norway signed in 2009.(120) The Monitoring, Reporting and Verification System (MRVS) has evolved over time, to accommodate new technologies, sensors, analytical methods and the importance of local management and capacity. Today, the MRV processes conform to IPCC Approach 3.(121) The data sets used for the change analysis have moved from the establishment of baselines required to monitor deforestation to the inclusion of data sets and the development of methods required to estimate and report degradation. Mapping of the 1990 forest extent was undertaken using Landsat imagery supported by 1991 JERS-1 radar data and historical 1960-era aerial photography. The latter data sets were used to verify the location of the forest/non-forest fringe and vegetation composition. Change analysis from 1990 to 2009 was conducted primarily with Landsat imagery, supported as required with IRS and CBERS images. After 2009, Guyana's MRVs as managed by the Guyana Forestry Commission(122) moved to annual reporting of deforestation. Under the Norway/Guyana agreement, the schedule of performance-based payments was referenced against the 2009 benchmark map that provided a snapshot of forest change as at 30 September 2009. The agreement imposed the constraint of including images acquired between August and December of each year. Given the persistent cloud cover and the temporal frequency of Landsat 5 (16-days) and image quality issues affecting Landsat 7 from 2011 onwards, these data sets were primarily superseded with fine resolution images from RapidEye. With a constellation of five satellites, RapidEye allowed higher temporal and spatial resolution (5 m). The advantages were twofold reducing risk of cloud obscuring change and improving the ability to assess degradation. From 2013 onwards, national degradation estimates where made using a two-stage stratified-random sample design to capture change in areas with medium and high risk of change. The data capture system is transferable to various models of a light aircraft and able to capture at 25 to 60 cm, a resolution capable of identifying forest degradation with some certainty.

Figure 12 shows the timeline of the various improvements made to the MRVs, including the shift to annual reporting, national estimation of degradation, improvements in the accuracy

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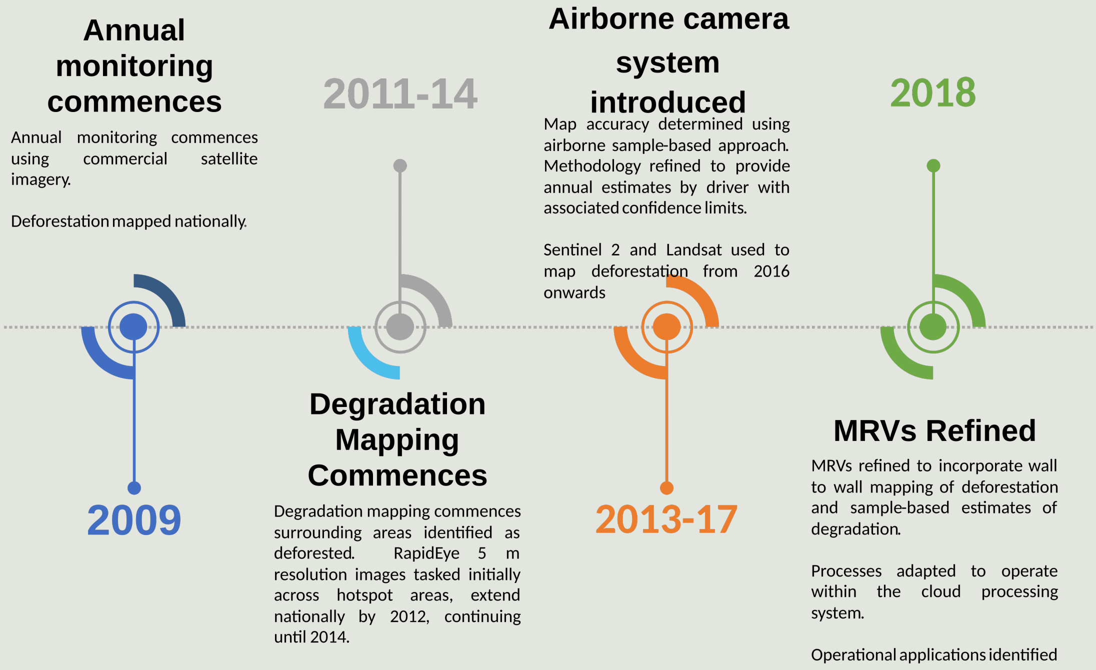
(120) The Joint Concept Note sets out a series of interim measures that are intended to be used whilst the full MRV functionality is being developed.

(121) **Guyana's MRVs 2009 to 2020**.

(122) The implementing Agency with technical assistance provided by Indufor Asia Pacific, New Zealand.

assessment processes, and lastly deployment of a low-cost Guyana-managed MRVs.

Figure 12: MRVs progressive improvement timeline



2009

Annual monitoring commences

Annual monitoring commences using commercial satellite imagery.

Deforestation mapped nationally.

2011-14

Degradation Mapping Commences

Degradation mapping commences surrounding areas identified as deforested. RapidEye 5 m resolution images tasked initially across hotspot areas, extend nationally by 2012, continuing until 2014.

2013-17

Airborne camera system introduced

Map accuracy determined using airborne sample-based approach. Methodology refined to provide annual estimates by driver with associated confidence limits.

Sentinel 2 and Landsat used to map deforestation from 2016 onwards

2018

MRVs Refined

MRVs refined to incorporate wall to wall mapping of deforestation and sample-based estimates of degradation.

Processes adapted to operate within the cloud processing system.

Operational applications identified

The MRVs is data-agnostic and provides a versatile platform that grows, develops and allows improvements as these became necessary. Progressive development has allowed time to bridge gaps in capacity, and the integration of alternative image sources and migration to cloud-based image processing and time series analysis routines. Today, the potential of the data generated through annual mapping of forest change extends well beyond the intended MRV function to include a range of national functions relating to policies, decision-making, integration of compliance functions, and more effective management within the natural resources sector.

3.1.2 Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) data are typically useful for the estimation of above-ground biomass. Microwave pulses are omitted obliquely, and in forest land, emitted pulses reflect from the ground, or canopy or trunk of woody plants and trees. Using the strength and other attributes of the reflected pulses, the acreage and above-ground biomass of woody vegetation, and their changes over time, can be estimated.

SAR is an active system operating in the microwave domain of the electromagnetic spectrum. Microwaves are not visible to the human eye and SAR satellites therefore provide a different, thus complementary, view of the ground compared with optical remote sensors. The radar emits an electromagnetic pulse and records the part of the pulse that is reflected, or scattered, back to the satellite (hence the term backscatter). Unlike sunlight, which is non-polarised and comprises a large range of different wavelengths, the radar is like a laser, but operates within narrow and well-defined wavelength bands in the microwave spectrum, with specific polarisations. As microwave signals are several magnitudes larger than optical light, they are almost unaffected by clouds, smoke and haze, making SAR an important tool in cloud- or fire-prone regions.

Common present and near-future (planned launch dates provided) spaceborne radar systems operated by CEOS agencies are listed below(123):

- P-band: 69.0 cm (*BIOMASS: 2022*)
- L-band: 23.5 cm (ALOS-2; SAOCOM-1; *ALOS-4: 2022; NISAR-L: 2022*)
- S-band: 9.4 cm (NovaSAR-1; *NISAR-S: 2022*)
- C-band: 5.6 cm (Sentinel-1; RADARSAT-2; RADARSAT Constellation Mission)
- X-band: 3.1 cm (TerraSAR-X; TanDEM-X; COSMO-SkyMed, PAZ)

SAR is sensitive to forest and vegetation structure, and the radar wavelength strongly affects what size objects can be detected. The radar signal typically interacts with objects of about the same spatial magnitude as the radar wavelength, and larger, while objects significantly smaller than the wavelength become transparent to the radar. The smaller the objects, the less influence on the backscatter. Consequently, longer wavelength radar signals (P-band, L-band) can penetrate through the leaves in a forest canopy and interact with the larger tree structures, such as the trunks and larger branches and hence display a limited positive correlation with aboveground biomass. Above ground biomass saturation may vary between 80 and 150 Mg/ha for L-band radar and 200-350 Mg/ha for P-bands (**Chapter 5, SAR Handbook**). Systems operating at shorter wavelengths (C-band, X-band) have limited penetration in dense canopy forests, but are more sensitive to sparse and low biomass vegetation.

The orientation of the radar wave (i.e. the polarisation) also affects the strength of the received signal, as the orientation and structure of the vegetation (e.g. vertical stems, randomly oriented branches, horizontal ground) in turn influence the orientation of the reflected (backscattered) signal. Current Spaceborne-radar systems operate with linear polarisation, where the radar signals are transmitted and received at horizontal (H) and/or vertical (V) polarisation. The different polarisation bands provide different information about the ground, very much in analogy with the various spectral bands of optical data. A SAR image is made up of the combination of three main type of scatters: rough surface scatters (low vegetation, bare soil); double-bounce scatters (tree trunks, buildings, light poles); and volume scatters (vegetation canopies). The strength of the backscatter of a given polarimetric channel (HH,

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(123) The radar band letters are of military origin and (hence) have no specific meaning.

VV or HV) would be enhanced, depending on the type of scatters observed. As a general rule of thumb, rough surfaces have enhanced scattering strength in VV polarisation, double bounce scattering in HH polarisation and volume scattering in HV or VH polarisation (e.g. Flores-Anderson *et al.*, 2019). Consequently, the use of at least two polarisations (HH+HV or VV+VH) is strongly recommended for most land applications.

As the concept of radar and microwaves is different from that of traditional optics, some basic understanding of SAR technology and how radar signals interact with different land cover types is recommended to properly utilise SAR data. CEOS has published a simple **SAR interpretation guide** to help users with little or no SAR experience get started. For a more in-depth background to SAR theory and forestry applications and tutorials, the **SAR Handbook: Comprehensive Methodologies for Forest Monitoring and Biomass Estimation** (Flores-Anderson *et al.*, 2019) is recommended.

3.1.2.1 Long wavelength band SAR systems

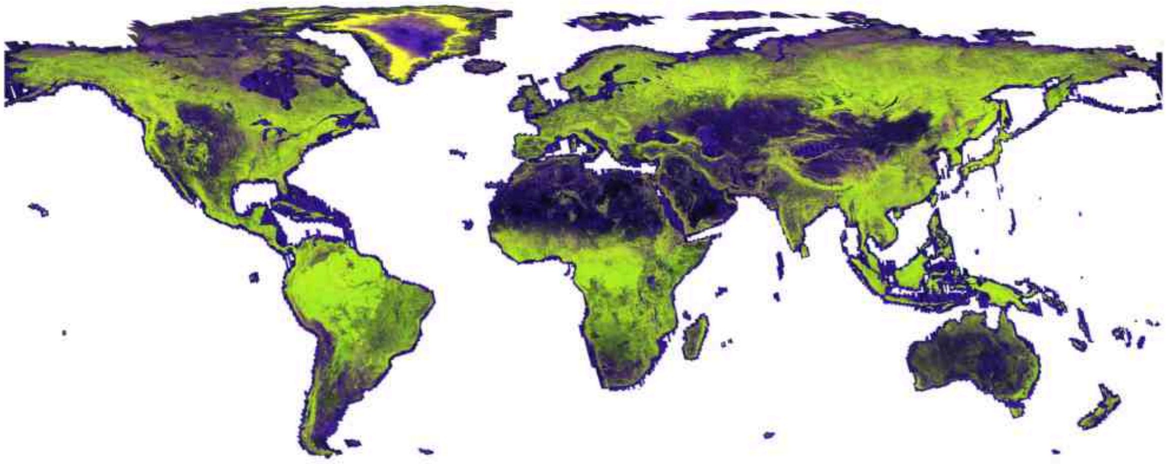
Long wavelength band radars typically refer to SAR systems operating at L-band or P-band frequency. L-band SAR systems are characterised by fair canopy penetration (when leaves << radar wavelength) and main backscattering occurring from twigs, branches and stems, thereby generally providing clear distinction between vegetated and non-vegetated areas. They are therefore suitable for the detection of changes in forest cover and estimation of the areas affected, and with time series at annual or semi-annual intervals, can support the provision of activity data. L-band backscatter correlation with growth stage/forest age classes also allows for mapping of regrowth.

L-band backscatter displays a positive correlation with above-ground biomass up to a level of about 100-150 Mg/ha, depending on forest type and composition: lower for natural/mixed forests, higher for homogeneous forests and plantations (a notable exception being palm trees (e.g. oil palm plantations), where the large palm fronds (i.e. leaves >> radar wavelength) prevent signal penetration through the dense canopy, resulting in a closer backscatter correlation with Leaf Area Index than with AGB (Rosenqvist, 1996)). Within the L-band sensitivity range, the data have been used for above-ground biomass estimation in a variety of low to medium biomass forest categories, including the Amazon floodplain (Pereira *et al.*, 2018) and secondary forests (Cassol *et al.*, 2018), African savannahs (Naidoo *et al.*, 2016) and woodlands (Bouvet *et al.*, 2018) and boreal forests in Siberia (Stelmaszczuk-Gorska *et al.*, 2019).

L-band SAR has for the past three decades constituted the longest radar wavelength available from space, with the Japanese JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2 missions providing systematic global observations in periods since the mid 1990s. The data have been assembled into annual global mosaics at 25 m pixel spacing, geometrically and radiometrically corrected (**Figure 13**). Annual global mosaics are generated continuously (presently by ALOS-2 PALSAR-2) and all historical and contemporary mosaics are available for free public download from the Japan Aerospace Exploration Agency (JAXA) **data repository**. All mosaics are planned to be reprocessed to comply with the CEOS Analysis Ready Data (**CARD4L**) format. Further public open L-band SAR data sets include coarser resolution (50-100 m) wide-swath (ScanSAR) data from ALOS PALSAR (2006-2011) and ALOS-2 PALSAR-2 (2014-present), acquired monthly/bi-monthly over the global pan-tropical zone. The full archives of data from ALOS PALSAR (fine resolution and ScanSAR) and ALOS-2

PALSAR-2 (ScanSAR) will be publicly released free of charge by JAXA during 2020.

Figure 13: ALOS-2 PALSAR-2 25 m global L-band SAR mosaic for 2018



Source: JAXA EORC

The importance of L-band SAR has been recognised by several CEOS agencies and sustained availability of L-band SAR systems is secured for at least the next decade, with the SAOCOM-1A/1B constellation (Argentina) in orbit since 2018, ALOS-4 (Japan) and NISAR-L (USA) scheduled for launch in 2022 (JPL, 2018), and ALOS-6 (Japan), the Copernicus High Priority Candidate Mission ROSE-L (EU) and Tandem-L (Germany) under development for launch in the latter half of the 2020s.

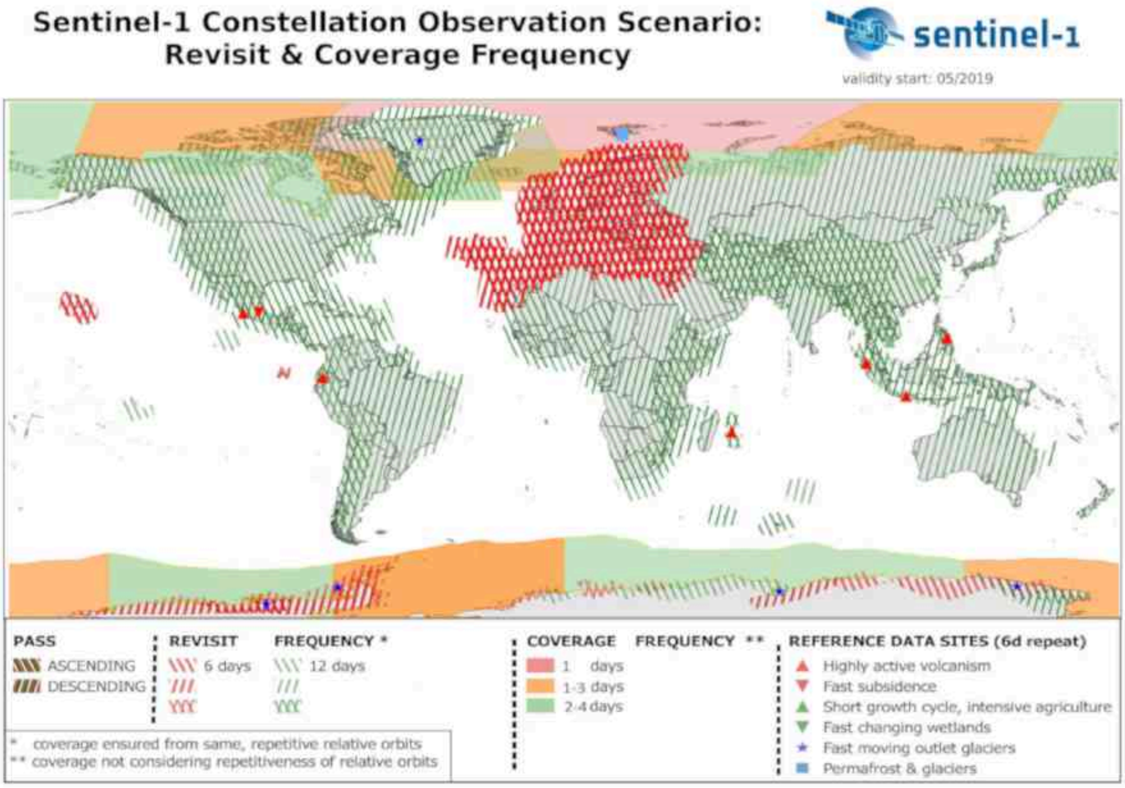
The European Space Agency's Biomass Earth Explorer mission (BIOMASS), with planned launch in 2022, will be the first Spaceborne P-band SAR mission. With a wavelength almost three times that of L-band, backscatter sensitivity with above-ground biomass increases significantly. P-band data acquired over tropical forests by airborne sensors, collected using the same (tomographic) acquisition geometry as that to be used for BIOMASS, indicated sensitivity beyond 400 Mg/ha, with no apparent signal saturation detected (Le Toan and Quegan, 2018). Biomass is a scientific mission, set out to measure the worldwide distribution of forest above-ground biomass and forest height in order to reduce the major uncertainties in carbon stocks and fluxes associated with the terrestrial biosphere. During its planned 5-year mission life, near-global maps of aboveground biomass (North America and Europe excluded) and forest height at 200 m resolution will be generated at 7-month intervals (Quegan and Carreira, 2019). Biomass data and products will be provided by the European Space Agency free of charge in the public domain.

3.1.2.2 Short wavelength band SAR systems

Short wavelength radars commonly refer to instruments with wavelengths < 10 cm, most often meaning SAR systems operating at C-band and X-band, but also including the S-band frequency. C-band microwave signals typically interact with leaves and twigs in the top layer of the forest. While signal penetration is generally limited in dense canopy forests, C-band is complementary to L-band (and P-band) in sparse and open forest areas, and is sensitive to low biomass vegetation, such as early regrowth, bushes and shrubs, where the longer wavelengths display limited sensitivity. The use of dual polarisation data (VV+VH or HH+HV) is a prerequisite to enable vegetation mapping with C-band SAR, as is access to adequate time series of data.

With a free data policy and global acquisition strategy, the Copernicus Sentinel-1 mission provides C-band SAR for land applications. Launched in April 2014 (Sentinel-1A) and April 2016 (Sentinel-1B), the constellation provides dual polarisation (commonly VV+VH) observations at dense temporal frequency for all global land areas every 6-days for Europe and neighbouring regions and every 12-days the rest of the global landmass (**Figure 14**). With about 30 acquisitions every year, it presents an opportunity to reduce speckle (thus improving effective spatial resolution) and background noise caused by various environmental factors (such as rain) that affect the radiometric stability of the backscatter. Sustained availability of Sentinel-1 data is guaranteed well into the 2030s, with each Sentinel-1 satellite having a design mission lifetime of 7-years (and fuel for 12-years). The Sentinel-1C and -1D follow-on missions are currently under development. To maintain the high temporal acquisition frequency, at least two Sentinel-1 satellites will be in orbit at any one time. Data from the Sentinel-1 mission are being distributed with a free and open data policy and can be accessed through the **Copernicus Data Hub,** as well as from other hubs such as the **Alaska Satellite Facility**.

Figure 14: Sentinel-1 C-band SAR global observation scenario



Source: Copernicus

Other short wavelength mission include the C-band Canadian Radarsat Constellation Mission (RCM) with a public open data policy; the X-band German TerraSAR-X/TanDEM-X, the Italian COSMO-SkyMed 3-satellite constellation; the Spanish PAZ; and the S-band NovaSAR-1 satellite of the U.K., launched in 2018. Annual NovaSAR-1 observations over Australia and the Pacific region in dual polarisation (HH+HV) mode will be publicly open and available in CEOS Analysis Ready Data (**CARD4L**) format from the **CSIRO data repository**. NovaSAR-1 data over other parts of the world will be publicly available from the **UK Satellite Applications Catapult**. The US-Indian NISAR mission, which will feature both L- and S-band SAR capacity, is scheduled for launch in 2022.

3.1.2.3 Data synergy

Demonstrating the advantages of data synergy, the European Space Agency **CCI Biomass** project (Santoro and Cartus, 2019) is using a combination of L-band and C-band SAR data, together with

LiDAR (ICESat GLAS) and auxiliary map data for the generation of global maps of above-ground biomass for the years 2010, 2017 and 2018, corresponding to the availability of historical ALOS and ALOS-2 L-band SAR mosaic data and C-band data from Envisat and Sentinel-1. New data sets from recently launched LiDAR sensors (GEDI and IceSAT-2) will be integrated in the 2018 follow-on maps. The mapping aims to achieve 500 m - 1 km spatial resolution, with a relative error of less than 20 percent where aboveground biomass exceeds 50 Mg/ha. Although this resolution is finer than required for current climate modelling, the objective is to allow more refined information to be inferred (e.g. forest age structure and the disturbance regime) that is relevant for climate and has the potential to be exploited by carbon cycle and climate models as they develop. The first global aboveground biomass map, for the year 2017 with 100 m spatial resolution, was released in 2019. It is available together with per-pixel estimates of aboveground biomass uncertainty for public download via the CCI Open Data Portal on the **CEDA Archive**.

3.1.3 LiDAR

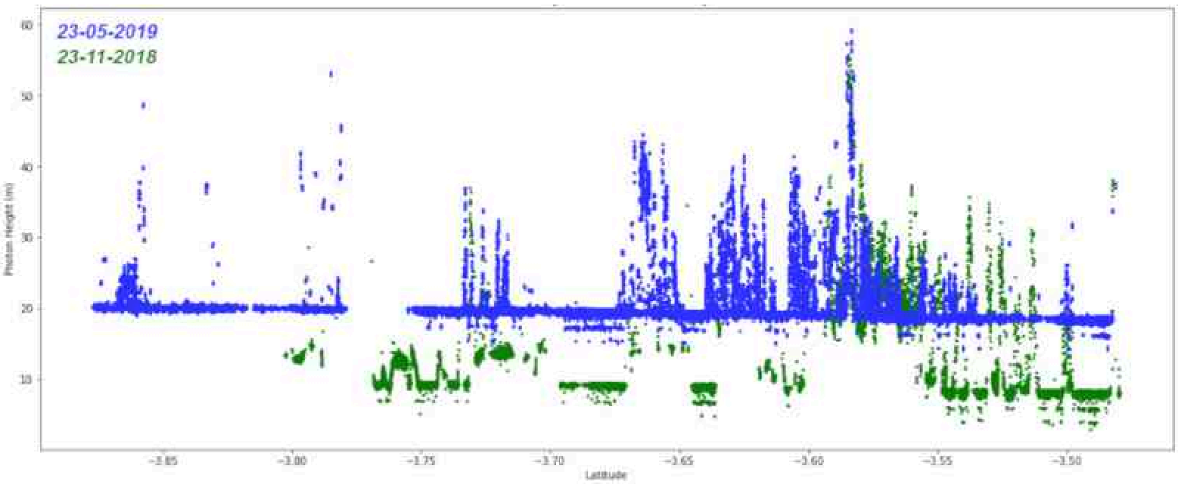
LiDAR (Light Detection And Ranging) is an active remote sensing technology (the optical version of radar) which uses pulses of laser light to measure distance and (in some cases) reflected energy. The laser altimeter instrument emits light pulses that interact with different strata of the vegetation and from which quantitative information on vegetation vertical structure can be estimated. As LiDAR systems provide direct measurements of ground and vegetation height, they are highly relevant for the estimation of emission factors. There is significant promise to use LiDAR (point) observations to calibrate and validate estimations of forest stand height and above-ground biomass derived from SAR (wall-to-wall) data to improve analysis feasibility and accuracy (Siqueira, 2019; Saatchi, 2019).

3.1.3.1 Spaceborne LiDAR

Since 2018, two spaceborne LiDAR missions have been in operation: the Ice, Cloud and Land Elevation Satellite 2 (ICESat-2) and the Global Ecosystem Dynamics Investigation (GEDI) mission. While the spaceborne systems do not provide continuous spatial coverage (unlike many airborne systems), they instead provide point measurements on or along the spacecraft ground track. Two of their main advantages are (1) their ability to collect data globally over all countries; and (2) the fact that all data are publicly available free of charge. Spaceborne LiDAR data are often used in combination with optical and/or SAR satellite imagery to interpolate estimates between the LiDAR transects or footprints (Scarth *et al.*, 2019). While the LiDAR instruments operate in the visible and near infrared part of the spectrum, and cloud cover will therefore affect data acquisitions, cloud interference can be expected to be mitigated over time as the instruments continuously collect data during their mission lifetimes.

ICESat-2 provides global measurement at 3-month (91-day) intervals, with 30 km between adjacent ground tracks at the Equator. It carries a photon-counting laser altimeter (ATLAS) that operates at 532 nm (green) wavelength. The instrument emits 10 000 laser pulses per second (pulses/s) compared to 40 pulses/s for the GLAS instrument on ICESat-1 which corresponds to measurements every 70 cm along the satellite's ground path. The travel time for each reflected photon (out of about 20 trillion photons per pulse, only about a dozen return!) is measured and the distance calculated, resulting in a vertical cloud of height measurements along the satellite nadir path. ICESat-2 products include estimates of terrain height, canopy height, and canopy cover at 100 m fixed-length steps along the ground track (**Figure 15**).

Figure 15: ICESat-2 photon height measurements along a river-forest transect



ICESat-2 became operational in 2019 and has a nominal mission lifetime of 3-years, with possible extended operations depending on instrument performance. ICESat-2 data at various product levels are available for public download from the **National Snow & Ice Data Center (NSIDC)** and in simpler formats from **OpenAltimetry**. Historical ICESat GLAS data collected between 2003-2009 are also available from the same locations.

GEDI is a near-infrared (1064 nm) LiDAR deployed on the International Space Station (ISS) in April 2019 for a nominal 2-year mission(124). The ISS orbit provides coverage between 60 degrees South and North latitude. As the ISS orbit is not sun-synchronous, the ground tracks do not produce a fixed repeat pattern (e.g. in contrast to ICESat-2). On the one hand this results in no specific point on the ground being measured more than once, but on the other, it means that measurements are sampled with greater geographical coverage.

GEDI is a so-called full-waveform LiDAR, which in addition to ground- and vegetation height, also measures the amount of laser energy reflected by plant material (stems, branches and leaves) at different heights above the ground (**Figure 16**). The waveforms are processed to provide metrics for each footprint, such as terrain elevation, canopy height, relative height metrics and Leaf Area Index. These measurements are also used to quantify aboveground biomass density at the scale of individual GEDI footprints, each of which is approximately a 25 m diameter circle containing information on the vertical profile of the vegetation (**Figure 16**). Statistical models and field inventories are used to predict aboveground biomass density, and its associated uncertainty, at the location of every profile measurement. GEDI footprints are collected in a sampled manner with 8 footprints spaced across a

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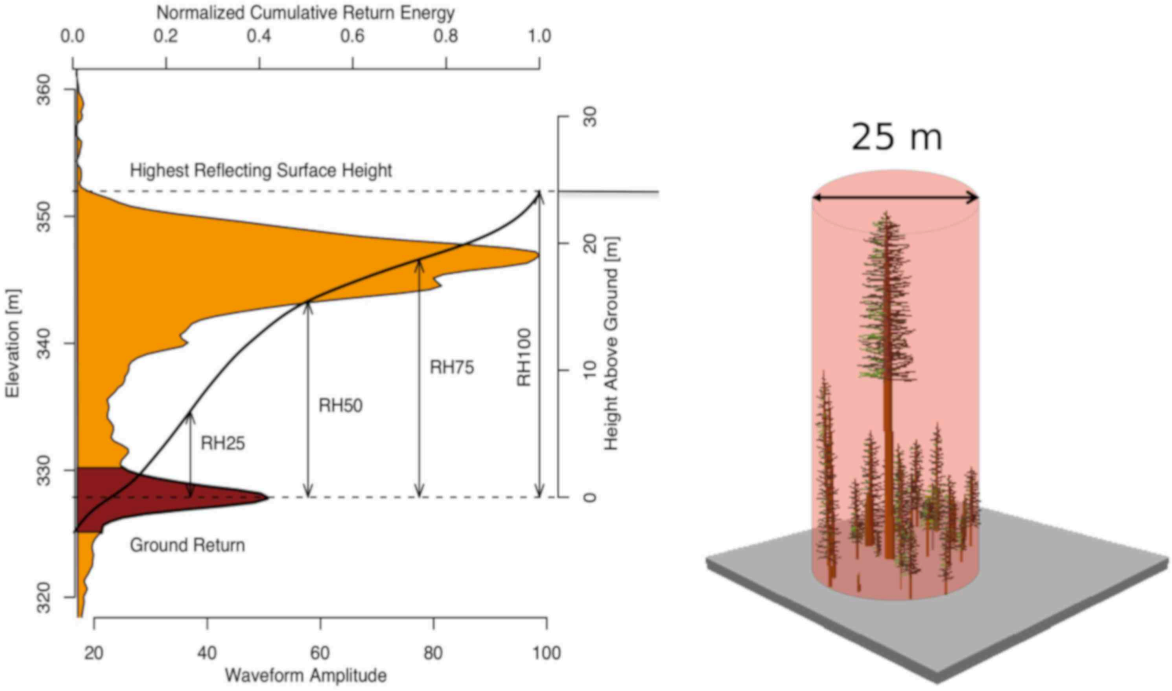
(124) The Multi-footprint Observation LiDAR and Imager (MOLI) is spaceborne LiDAR mission under consideration by the Japan Aerospace Exploration Agency (JAXA) for deployment on the International Space Station around 2024. Potentially providing important continuity to the GEDI mission, MOLI is also a full waveform LiDAR operating at near-infrared (1064 nm) wavelength. The dual-beam laser is designed to provide 25m waveform footprints sampled at 50 m intervals along two parallel ground tracks. To aid interpretation of the LiDAR data, MOLI will also carry a traditional (push-broom) optical imager that will provide simultaneous (green, red and infra-red) images along the LiDAR ground track.

4.2 km swath, collected at 60 m intervals.

Figure 16: Full LiDAR waveform as measured by GEDI



Source: GEDI Ecosystem LiDAR, 2020

All GEDI data products are available for free public download. Lower-level data products (geocoded waveforms and footprint level canopy height and profile metrics) are available from the **NASA/USGS LPDAAC**, and higher-level products (gridded canopy height and uncertainty metrics, and model-based above-ground biomass estimates) are available from the **ORNL DAAC** repository.

3.1.3.2 Airborne LiDAR Systems

In addition to spaceborne instruments, LiDAR measurements are obtained from airborne instruments. Collecting LiDAR measurements from aircraft is typically referred to as airborne laser scanning (ALS), and has a long history of operational use in forestry applications in developed countries (e.g. Næsset, 2002; Wulder *et al.*, 2012). The use of ALS is less common in the tropical forests because of a higher diversity of tree species, the complexity involved in analysing the data, and the cost of routine collection of LiDAR measurements. Still, a few examples are noteworthy:

- **Brazil -** Airborne LiDAR data, forest inventory data and various satellite data were collected across Brazil for construction of wall-to-wall maps of aboveground biomass in support of Brazil's national greenhouse inventory (IPCC, 2019). In an approach similar to that of Saatchi *et al.* (2017), LiDAR data were collected in randomly selected transects (n = 1,000) in which 407 field plots were selected. Biomass estimated in transects were extrapolated to create wall-to-wall maps using surface reflectance, radar data and precipitation data collected from various satellite missions.
- **Democratic Republic of Congo (DRC) -** Airborne LiDAR data were collected across the DRC in 216 randomly selected transects for estimation of aboveground biomass (Xu *et al.*, 2017). Biomass was measured in 91 field plots selected within the transects to establish relationships between the LiDAR measurements and biomass. Maps of biomass were created by establishing

a relationship between the LiDAR signal and various wall-to-wall data sets collected from satellite (ALOS/PALSAR, Landsat and MODIS). The sampling was designed to provide biomass estimates at national and subnational level and by forest type in support of REDD+ in DRC (Saatchi *et al.*, 2017).

- **Nepal -** A comparison between the use of airborne LiDAR, fine resolution RapidEye satellite data versus conventional ground-based techniques for estimating above-ground biomass (LAMP) was conducted in Nepal in 2011. LiDAR plots, wall to wall Rapid Eye satellite images, and in situ measurements from 738 field sample plots were used to estimate AGB. This was compared with field based multisource forest resource assessment (FRA) of 676 plots conducted in the same year. The results show that the biggest difference between the two approaches is spatial resolution. LAMP was more precise over a smaller spatial extent compared to conventional multisource forest inventory. Whilst the LAMP approach achieved higher precision, the FRA approach had lower baseline data collection costs.
- **Tanzania -** Airborne LiDAR measurements were collected repeatedly in systematically selected transects across Liwale district in Tanzania in 2012 and 2014 in a research project funded by the Norwegian Government. The project was not part of the establishment of Tanzania's official reference level under UNFCCC, which was based on Landsat and NFI data, but was an attempt to test and showcase operational use of ALS for estimation of aboveground biomass and carbon stock change in tropical conditions. While the project objectives were met, it is worth noting that Tanzania has not incorporated ALS into their national forest monitoring system. The project is described in detail in Ene *et al.* (2016) and Ene *et al.* (2017).

3.1.4 Global forest cover change data sets

Global maps of forest cover change and land cover, such as Hansen *et al.* (2013),(125) (observed (bio)-physical cover on the Earth's surface), are readily available and can add value at the National level when applied appropriately.(126) These maps include both static maps of a one-time period, as well as maps showing multiple time periods (dynamic/change) products. Land cover maps can have several thematic classes (ranging from few broad classes, to multiple classes and sub-classes), or can focus on just one broad class, such as forest cover. In the context of REDD+/forest MRV, these data sets have particular relevance, as they provide a stratification of any study area in the world (**Section 4.2.3**).

A more accurate map will serve as a more efficient stratification. 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, for example, by cloud cover; better quality observations, and more observations will improve accuracy). In general, it is hypothesised that the use of global maps for stratification purposes will produce activity data estimates with lower precision than are attainable by national mapping of comparable quality for stratification purposes, because the latter can be tuned to national forest definitions and make use of knowledge and auxiliary data available at national level. The precision of activity data estimates

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(125) This section is based largely on Use of global tree cover and change data sets 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 data sets for national REDD+ measuring and monitoring, Wageningen University, November 2015**.

(126) Available relevant land cover data sets include Hansen *et al.* (2013)**https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.6.html** at 30 m, Chen *et al.* (2014)[]](**http://www.globallandcover.com/** at 30 m, and Buchhorn *et al.* (2019)**https://land.copernicus.eu/global/products/lc** at 100 m. A global data set at 30 m resolution of land cover and land-cover change, including the IPCC land categories, is currently being produced at **Boston University**.

depends on the combination of the efficiency of the stratification (whether global or national) and the sample size of the reference data. Because of this, lower accuracy associated with global data sets can be compensated by the use of a larger reference sample, and global data sets may enable progress to be made until national mapping capacity is established. Global data sets and national mapping capacity can therefore be seen as complementary. A comparison between the use of global and local data sets for mapping deforestation is presented in Harris *et al.* (2018).

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

- Decide the precision required, and design the sampling-based effort accordingly. This is likely to depend on the policy context, including expectation in the context of results-based payments. Discussion between technical experts and policy colleagues on what can be achieved cost effectively may be needed.
- Obtain an initial, exploratory reference data set.(127)
- 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 (**Box 26**) is a measure of the improvement in precision obtainable by using map data and reference data in combination. Consideration of relative efficiency can help in deciding on 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; and
- 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, 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,(128) 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.

Rules to map the extent of the minimum percentage crown cover(129) specified in the national forest definition could be implemented automatically in some products, as percentage crown cover is a pixel-level attribute. However, some studies indicate that a given crown cover (say 30 percent) in

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(127) 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.

(128) 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.

(129) The relative performance of global and national classification methods may be a function of the crown cover threshold used in the national forest definition.

the national forest definition may not correspond to 30 percent as estimated in the global data set (Sannier *et al.*, 2016; McRoberts *et al.*, 2016a). 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(130) 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.(131)

Global map products indicating areas where tree cover has been removed entirely can be used to help map forest/non-forest land-cover change. However, areas where complete overstorey removal 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. Tree cover that temporarily falls to zero or below the minimum threshold (due, for example, to fire, wind, disease or harvest) does not entail a change from forest land use if subsequent replanting or natural or assisted regeneration take place.

Use of global data sets 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. Modifications introduced via auxiliary data need to be treated consistently over time, or significant error may be introduced into mapping and area estimation.

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. However, 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),(132) strata should be applied

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(130) 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 characterising 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.

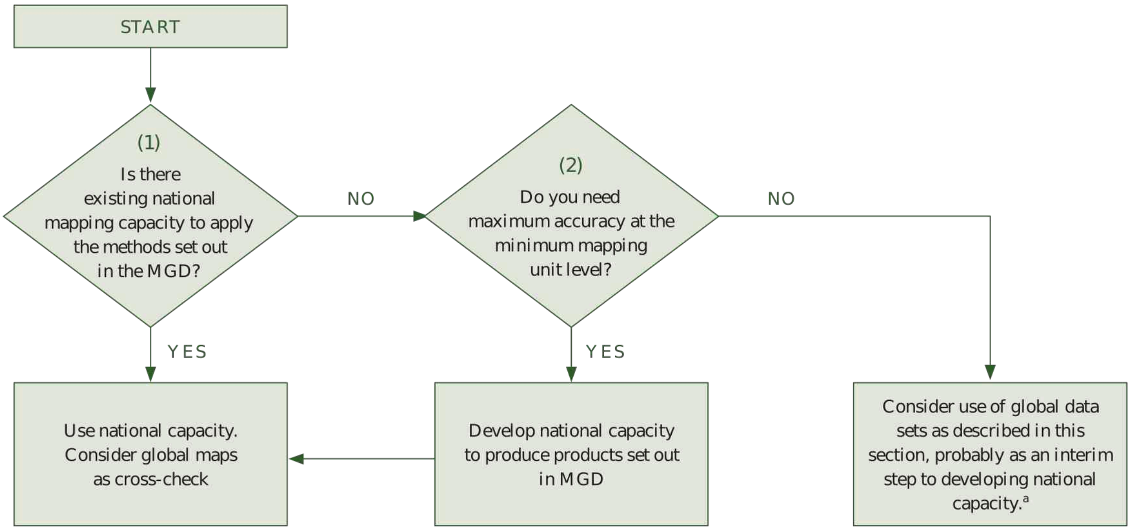
(131) Although the Australian National Greenhouse Gas Inventory approach to reporting land use, land-use change and forestry does apply such methods.

(132) 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 (**Section 4.3.1.2**).

consistently over time irrespective of whether national or global map products are being used.

Guidance on decision points to users as it pertains to the use of global maps are summarised in the decision tree **Figure 17** 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 17: 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 to this decision identified in the text include preferences for national ownership, cost relativities, of national mapping or global data sets plus increased reference sample size and ability to respond to technological developments.

Considerations for 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 remotely sensed data are outlined in 4 and 5. All cases assume joint use of mapped and reference data. Note that existing capacity is also a question of cost effectiveness. If a country lacks the resources to build capacity for creating national maps in the long term, the answer to Decision Point 1 is **No**.

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 subnational activities.

Box 26: 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 4

$$RE = \frac{\widehat{V}(\widehat{\mu})}{\widehat{V}(\widehat{\mu}_{map})}$$

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 5

$$n(n_1 - 1)p > M$$

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 it 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 its accuracy. 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 B**, 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 percent to 90 percent for area estimation, and by 50 percent to 80 percent for area change estimation (**Table 29**).
- Compared with using a reference data sample alone, use of a national map to estimate forest area can reduce the sample size by over 95 percent whereas use of global mapping can reduce sample size by 85 percent to 95 percent When assessing change in forest area, the same study suggests a 10 percent 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 percent reduction in sample size is observed when the national map is used during the 1990-2000 period (**Table 30**).
- In Gabon, use of global maps uncalibrated to local conditions in estimating forest area have been shown to reduce sample size by between zero and 35 percent whereas use of maps calibrated to national forest definition were shown to reduce sample size by 30 percent to 50 percent (**Table 31**).

The relative efficiency of using remotely sensed data depends on many factors, such as 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 that 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.

3.1.5 Considerations for remotely sensed observations

As indicated in **Section 1.2.3**, one key strategic element for a sustainable NFMS is the effective use of resources. The selection of the most adequate source of remotely sensed data plays a key role in ensuring a sustainable NFMS, since it may affect the capability of the NFMS to generate the necessary data (**Section 1.2.2**) and will affect the infrastructure required for data processing (**Section 1.3.3**). Considerations for remotely sensed observations will differ depending on whether land cover or land-cover change maps are produced, reference data are collected, or biomass predicted or estimated.

3.1.5.1 Land cover and land-cover change maps

Land cover and land-cover change maps are important tools for policy making, program design and monitoring program implementation, and experience shows that they are useful for reducing uncertainty in area estimates (GFOI, 2018) by serving as a source of stratification; the higher the accuracy of the map the higher the efficiency of the stratification. For the production of land cover and land-cover change maps, several criteria should be considered to select the right source of remotely sensed data:

- **Thematic discrimination -** For the thematic discrimination of forest land from the other land-use classes, optical sensor types with the Visual and Near Infrared (VNIR) and Shortwave Infrared (SWIR) spectral bands have more stable information content than sensor types with just VNIR or SAR. However, in dry forests the use of SAR, in particular L-Band, improves thematic discrimination of forests (**Box 27**) and can be used to complement optical sensors (Reiche *et al.*, 2015),
- **Minimum mapping unit (MMU) -** This is closely related to the minimum area of the forest definition and the spatial resolution. The optical sensors of the Landsat missions have around 30 m of spatial resolution, 0.09 ha of pixel size, which would mean it could be possible to identify areas of forest of this size. However, it is worth noting that reliable thematic information should not rely on information deduced from a single pixel due to the signal/noise ratio(133) and has to be aggregated within a minimum of one pixel in each direction of the target pixel (i.e. box of 3 by 3 pixels = 90 m x 90 m in Landsat, which is close to 1 hectare).
- **Temporal resolution, clouds and seasonality -** The availability of Landsat 8 and Sentinel 2 has created an unprecedented availability of data, resulting in a global median average revisit interval of 2.9-days (Li and Roy, 2017). Cloud cover can create challenges for regular land cover mapping in many tropical regions, and this can be compensated by an increase in temporal resolution that enables gaps in information to be covered. Seasonality, caused by a protracted dry season and predominance of deciduous trees, results in a strong annual cycle of leaf display, which can be difficult to characterise in imagery and can lead to detection of spurious changes due to interannual cycles. These cycles may be correctly characterised with a sufficient temporal resolution. SAR data are a useful alternative in areas of persistent cloud cover.
- **Accessibility -** Stable, secured and easy access to remotely sensed data and processing capabilities is an important criterion to be considered, in order to ensure the correct functioning of monitoring systems. Many missions, such as Landsat and Sentinel, have an open data policy that enables free access to their data; access is facilitated through different portals and means, making data accessible when needed. Currently, options to pre-process and process these data in

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(133) Unless the relative spectral discrimination power between the thematic classes is high, which depends on the local conditions.

the cloud (**Section 1.3.3**) are available, but it is important to understand whether these processes will be accessible in the future, and the related risks. Not having access to the data and processing capabilities in a timely manner could represent a significant risk that should be considered in decision-making (e.g. a compromise on accuracy may result in improved consistency).

- **Historical coverage -** The establishment of reference levels and the ability to map changes on the land surface require historical data. Currently, Landsat is the only satellite mission that can provide data for almost any point on Earth back to year 2000 (**Section 3.1.1**), but this situation will change as the records of other satellite systems grow.
- **Cost -** Cost of access and processing is one of the key aspects to be considered by countries when selecting the remotely sensed data to be used. Careful consideration on the cost/benefit ratio for current and future use should be made, as well as the availability of funds to cover these costs in the future. Additional benefits could be related to an increased thematic discrimination, and spatial and temporal resolution, but it should be clear that these benefits can compensate for the additional costs incurred.
- **Future perspective -** The future perspective for acquisition of imagery and processing is an important criterion for selecting the source of remotely sensed data. The NFMS should generate data in a systematic and consistent manner, and for this the use of imagery with similar standards is important, as well as the continuous availability of tools to process it. While Landsat and Sentinel mission continuation is guaranteed for the next decade (**CEOS, 2020**), the continuation of other missions or the generation of global products might not be secured. The same applies to tools for which development and maintenance might be discontinued.
- **Country ownership of the data -** It is important that all data are fully endorsed and accepted through the NFMS **institutional arrangements**.

Box 27: Particular considerations for Forest monitoring in the dry tropics

The dry tropics, where vegetation is characterised by savannahs, woodlands and dry forests, poses particular challenges for forest monitoring. Typically, lower accuracies can be expected from Earth Observation based mapping in these vegetation types, with complications associated with:

- **Seasonality -** A protracted dry season and predominance of deciduous trees result in a strong annual cycle of leaf display, which can be difficult to characterise in imagery. This cycle can show interannual differences in leaf display, driving detection of spurious changes. In savannahs, grasses and tree canopies have separate and overlapping phenological cycles, which are challenging to separate in a time series.
- **Landscape heterogeneity -** Vegetation structure varies over small spatial-scales, with closed-canopy forest and open savannahs co-existing in a landscape. The signal associated with forest and forest change will usually differ between these vegetation structures.
- **Fires -** Fires are very common in savannahs during the dry season, causing abrupt changes to surface properties that are not usually associated with deforestation or degradation.
- **Small magnitudes of change -** Lower tree canopy cover in the dry tropics means that changes to tree cover are inherently of smaller magnitude, and therefore harder to detect.

Experience with the four above issues in three dry forest countries in southern Africa: Mozambique, Namibia, and Zambia served to provide the following guidance that should be taken into consideration by countries:(134)

- **Land use/cover mapping -** Optical images (e.g. Sentinel-2) should be selected from a consistent time of year (e.g. wet season, early dry season), taking into account seasonality in vegetation phenology, fire occurrence, and cloud cover. Stacking of composite images from multiple seasons can improve the separability of vegetation types, where their phenological cycles differ. Inclusion of radar imagery in a classification can aid discrimination of land-use categories (Joshi *et al.*, 2016) (e.g. Sentinel-1), and long-wavelength radar can aid characterisation of forest cover (Naidoo *et al.*, 2016) (e.g. ALOS PALSAR 1/2, NISAR).
- **Biomass mapping -** There is a well-explored relationship between L-band radar backscatter and aboveground biomass in the dry tropics (Mitchard *et al.*, 2009), which unlike in dense tropical forests, does not usually saturate. Biomass change can indicate deforestation, degradation, and (re)growth (McNicol *et al.*, 2018).
- **Change detection -** Satellite time series have yet to produce consistent land-cover change information in the dry tropics, unlike in denser forests. Difficulties in the detection of forest change can be mitigated through comparison of imagery from the same season, for example classification of change using composite images from the wet season where leaves are displayed. Image normalisation can assist the detection of change where seasonality is inconsistent, including 'spatial normalisation' in heterogeneous landscapes (Hamunyela *et al.*, 2016). Where available L-band radar backscatter change can offer an alternative approach to classifying change in areas of moderate canopy cover, and is particularly favourable where optical images are influenced by the co-existence of trees and grasses.

The monitoring strategy employed should take account of the properties of the vegetation being monitored. Owing to their structural variation, no single monitoring strategy will be fully applicable to the whole dry tropics. Sub division into regions with similar vegetation types may be necessary, allowing the application of locally appropriate monitoring methods.

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(134) See the **SMFM Project** for details of experience from the testing of tools in three dry forest countries.

3.1.5.2 Reference data

As explained in **Section 4.2.3**, reference data refer to data that represent the ground reference conditions, and this is crucial to enable the estimation of areas in accordance with IPCC guidelines. Although some of the considerations presented above may also apply to the reference data, additional considerations should be taken into account:

- **Source of reference data -** Reference data may be collected by direct observations of ground conditions by field crews or by inspection of satellite data and aerial photography. While possible, data collection for area estimation through field inventory is often logistically difficult and/or cost-prohibitive and remote areas may even be inaccessible, especially in tropical countries. For these situations, reference data in the form of interpretations of satellite data and in some few cases airborne orthophotos are often used. The reference data must be of at least the same and preferably of greater quality than the map data with respect to both spatial resolution and accuracy (Olofsson *et al.*, 2014). However, if finer resolution imagery is not available, a careful and manually interpreted sampling unit should be more accurate than an automated classification, even if both are using the same source of data. Human interpretation may bring in information about spatial context and structure, which is often difficult to incorporate in automated machine-based methods. However, it is important that the interpreters use all resources available that would give them enough information and context to be able to classify the sample with confidence. For instance, looking at dense time series of imagery (e.g. data from the Landsat archive) even looking at imagery from before or after the period of analysis should provide in most cases contextual information to be able to observe reference conditions at the location of sampling units. The use of time series data is especially important when collecting observations of land change. For example, examining all available Landsat observations in different spectral bands at sample locations greatly enhances the ability to determine if, and how, the land surface has changed. Different packages such as **Collect Earth Online** or **AREA2** enable access to multiple sources of satellite imagery, ranging from fine resolution imagery to time series of Landsat and Sentinel archives.

- **Quality of data collection -** The quality of the reference data sets should be carefully controlled to ensure the greatest level of quality. As mentioned, this can be achieved through the use of finer resolution and more detailed analysis of available source data. There should also be a proper quality assurance process in place to minimise both systematic and random interpreter error through a double interpretation process and calibration at the start of process, which can be gradually reduced as the differences between individual interpreters decrease to the point when they can be considered similar. Regardless of the quality of the resources and the experience of the interpreters, some additional uncertainty will result from using interpretations as reference data. Recent research shows that measurement variability and bias induced by inconsistent interpretations can be significant in land cover interpretation (Pengra *et al.*, 2019; McRoberts *et al.*, 2018c). Imperfect reference data could have substantial impacts on the estimate of change (Foody, 2010).

- **Minimum mapping unit and forest definition -** The minimum mapping unit is closely related to the minimum area of the forest definition and the spatial resolution. However, for collection of the reference data there are additional considerations to be taken into account, which are related to the response design. When collecting the reference data, different sampling units, different support units and different rules may be applied in the labelling protocol, leading to different results in terms of reference condition. **GFOI, (2018)** provides a number of examples of the most common approaches used in different contexts, and their implications. Careful consideration of the minimum mapping unit, operationalisation of the forest definition, the response design and its implications should be made.

3.1.5.3 Biomass estimation

Synthetic Aperture Radar and **LiDAR** provide additional information on the structure of the forest canopy that enables a prediction and estimation of biomass based on these metrics. Considerations of accessibility, cost and future availability should also be taken into account for biomass estimation. In addition, technical aspects related to the capacity of using the data from these sensors to predict and estimate biomass should be considered. The use of biomass maps constructed from remotely sensed data is discussed in greater depth in **Section 4.3.1.2**.

3.2 Ground-based observations

Ground-based observations are needed for the assessment of carbon pools, carbon dioxide, and GHG emissions and removals for REDD+ activities, regardless of the sampling or inferential method used. They are also important for calibration of algorithms for processing remotely sensed data and as reference data in conducting accuracy assessments of processing techniques.

Ground-based observations are used to estimate emissions and removals factors, establish growth models for different types of forests, parameterise Tier 3 models and estimate activity data in combination with change maps. It is important to consider the relationship between ground data and remotely sensed data with respect to how they will be used and combined in an NFMS, in particular, the compatibility of the geometry of the ground plot and that of the pixel or the minimum mapping unit (MMU) of the remotely sensed data.

Although availability will differ from country to country, examples of relevant ground-based observations include:

- National Forest Inventories, subnational forest inventories, and forest assessments based on plot or transect measurements.
- Growth and yield studies, harvested wood removals, and tree biomass modelling studies.
- Data on land use, management, disturbance history, and soil type, all of which can be used to guide the selection and application of emissions and removals factors.
- Data from research plots that can be used to estimate emissions and removals in above- and belowground biomass, litter, deadwood and soils.
- Field observations which can be converted to emission/removal factors for non-CO_2 GHGs from soils and fire.

Each of these examples can be categorised into one of three types of ground-based observations that are described in this chapter: National Forest Inventory data, intensive site monitoring data, and other data.

Under REDD+, the choice between the stock-difference method and the gain-loss method for estimating emissions and removals depends on the time series of existing data. To use the stock-difference method NFIs, or other comprehensive ground sampling programs must have collected at least two cycles of data to estimate emissions and removals. However, because it can take several years for a newly implemented NFI to collect two measurements, most countries are not yet applying this method.

For the gain-loss method, emissions and removals factors can be estimated using data from NFIs, intensive monitoring sites, and other ground data. In general, it will be efficient for the NFMS to collate relevant existing information prior to commencing any further sampling, and to conduct a gap analysis to determine the most efficient sampling strategy for any additional ground data collection. Access to original data sets, data collection protocols, and documentation of data quality checks is 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 (**Section 2.3.1**).

3.2.1 National Forest Inventories

National Forest Inventories are conducted by many countries to maintain current estimates of the condition and trends of the countries' forest resources. NFIs are often implemented as part of an NFMS that collect ground observations, which are typically collected from plots established using a probabilistic sampling design, **remotely sensed observations** and **other data sources**, such as climate, topography, ownership, and factors related to drivers. Most NFIs report not only forest land area, but also the volume, biomass, and carbon of the nation's forests, as well as changes in those attributes over time. The number of plots and thus the amount of ground data collected by NFIs usually depends on the NFI's desired level of precision for estimating a particular attribute at a particular spatial scale, within a desired confidence interval (e.g. estimating nationwide forest biomass within +/- 10 percent at a 90 percent confidence level). The ability to distinguish between carbon pools depends on the specific implementation details of the NFI (e.g. whether soil carbon data are collected, and whether below-ground carbon stocks are estimated).

3.2.1.1 Ability to estimate emissions and removals

Many countries hold at least some NFI data that can be used to support emissions estimation for REDD+. Well-designed NFIs are based on probabilistic sampling designs, with well-understood statistical properties that allow error estimates to be interpreted and facilitate construction 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. NFIs increasingly include the dead wood pool, and some have started to acquire information on soil organic carbon and litter, although estimating temporal change in these pools is challenging. Though traditionally established for forest resource assessment (often in close collaboration with forest research institutions), most NFIs also gather information on ecosystem-related variables and when combined with other data sources (including interviews of landowners and residents) information on drivers of forest change can be determined. Implementation of 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.

The degree to which NFIs can provide useful data on emissions and removals for REDD+ depends on the number and type of measurements collected, the adherence of the NFI implementation to the requirements imposed by the sample design, and the relationship between sample size and the variability of the attribute of interest within the geographic reporting unit. For example, if only forested areas are sampled, then no Emission Factors for conversion to/from Forestland can be estimated, as the pre/post carbon stocks are not known. Also, if the NFI was designed to produce estimates of a particular attribute for the entire country, estimates for geographic sub-populations are likely to be less precise due to the smaller sample size. Where the sampling design is suitable and at least two measurement cycles have been completed, NFI data can be used to estimate REDD+ emissions and removals directly, using the stock-difference method. Nevertheless:

- Existing NFI sample designs might not be adequate for estimating changes in land use or land cover for REDD+ activities such as deforestation or forest degradation, which thus increases uncertainties in estimating emissions and removals for specific activities. Increased sample sizes and/or integration of remotely sensed data (**Section 2.4.2**) may be required to meet these goals.
- Although NFI sample plots are usually geo-referenced, and can thus be integrated with other data such as social surveys or GIS data, they do not generally deliver sufficient information to track REDD+ drivers.
- Unless the NFI includes observations of plots that do not meet the country's definition of forest, it may be difficult to identify the drivers of forest loss (e.g. conversion of forest to agriculture) and gain (e.g. afforestation of areas that were previously agriculture).
- Although an NFI for an entire country may be desirable, it is often logistically complex and expensive in large countries, especially those with large areas of non-commercial forest.
- Due to the extended inventory cycle lengths, countries are likely to adopt the gain-loss, rather than stock-difference method to estimate REDD+ emissions and removals.

A single cycle of NFI data can be used to support the gain-loss method and upon remeasurement can be used to directly estimate carbon stock change. Remeasurement of NFI plots provides many benefits. 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 to develop models of forest growth, debris and soil carbon that satisfy Tier 3 requirements for above-ground biomass as set out in the GPG2003. 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 construction and verification.

When repeated measurements are obtained on the same plots versus different plots each time, average annual change (and associated carbon change) can be estimated more precisely (see **Section 5.3.3.3 of GPG2003**). The timing of plot re-measurements within an NFI varies from just a few years in fast-growing environments to 5 to 10-years in slower-growing environments. Frequency may be less for environments that are more expensive to access and measure, or for forests with less 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. Heikkenin *et al.* (2012) describe methods for making more precise estimates using panel data and other data. Annual surveys also have organisational and funding benefits (**Chapter 1**).

Where NFI data are (or can be) grouped according to REDD+ activity, they are likely to be valuable sources of data to estimate emissions and removals factors for use with the gain-loss method, or to develop Tier 3 models of forest growth, debris and soil carbon using the stock difference method. 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 may be more appropriate to report the discrepancy transparently then modify the design and include all appropriate lands. The existing NFI data can probably still be used for calibration and verification of remote sensed data. In addition, the data can be used to construct and parameterise models for use with model-assisted or model-based inferential methods.

3.2.1.2 General characteristics

Forest inventory experience is much less in the tropics than in boreal and temperate forests. Long-established NFIs, mainly in temperate and some boreal forests, are well-documented with respect to the validity and completeness of the data, assumptions, and models. Tropical forests differ substantially from boreal and 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 precisely, across spatial scales ranging from local to landscape, and national to regional. Although new tropical NFIs do not have such long histories and may face additional difficulties with locating and remeasuring plots in hard-to-reach areas, lessons learned from forest inventories in non-tropical countries can help when making decisions about sampling designs, field protocols, and statistical estimators. FAO (2017) provides guidance on many aspects of NFIs.

Typically, NFIs use arrays of plots or clusters of sub-plots (**Section 3.2.1.5**) established as components of probability sampling designs across entire countries. Estimation based on probability sampling assumes that either all plots can be physically visited and have measurements collected, or if some plots cannot be physically visited (i.e. nonresponse plots), such plots are randomly distributed throughout the sample (**Section 3.2.1.6**). Observations and measurements on these plots vary, but always include the amount of forest cover and tree-level data such as species and diameter, which can be used with allometric models to predict volumes and biomass of individual trees (Lawrence *et al.*, 2010). Rather than measuring the height of all trees, consider measuring height on a range of sample trees in each plot. The missing tree heights can be estimated using height models based on the trees measured (e.g. Mehtätalo *et al.*, 2015). The tree-level predictions are aggregated to predict 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 (e.g. evidence of past disturbance), soil characteristics, and canopy characteristics (for example, Vesa *et al.*, 2010 describe soil sampling on several sub-plots per cluster). These NFI data are typically used to estimate forest population parameters, including those related to timber production or development, at precision levels considered relevant for national level planning. Existing NFI designs have been optimised based on trade-offs between desired levels of precision and expected inventory costs.

NFIs commonly use one of the following probability sampling designs: simple random sampling, systematic sampling, stratified sampling, or less frequently, double sampling for stratification. Probability sampling requires that each potential plot location has a positive, known probability of being selected for the sample, and that a randomisation scheme is used to select the sample. NFIs typically use the resulting data with unbiased estimators to estimate means, totals, changes and their variances. Estimates for subsets of the original forest area are possible if sufficient numbers of plots can be grouped into domains or strata. The number of plots required depends on variability of the population, the precision required, and the size of the estimation domains. For example, acceptably-precise estimates of areas of rare classes like deforestation would require more plots than would be required for common attributes. The natural tendency is to sample only the forested areas on maps (i.e. stratification into forest versus nonforest areas with no samples in nonforest areas; **Section 3.2.1.3**). However, because the forest area changes over time, increases or decreases in the area considered forest could violate design-based sampling principles and thus compromise the unbiased nature of the estimators. This problem may be avoided by expanding the NFI design to all land use types, or at least those that could become forested over time. Otherwise, the NFI will not be sensitive to afforestation or reforestation and will only detect loss of forest area. Furthermore, if the forest portion of the forest map is used as the population, the inventory relies on the tenuous assumption that the forest/nonforest map is correct.

NFIs based on systematic sampling are approximately spatially balanced and typically use grid systems with plots located at grid intersections or randomly located within grid cells. Systematic sampling helps to spread the sample across all conditions and typically improves precision. To meet the assumption that each potential plot location has an equal likelihood of being selected for sampling, grids must be established in an equal area projection, in order to avoid changes in the cells' area due to changes in latitude. Grids using latitude and longitude are to be avoided, since they do not result in equal-area grid cells in the north-south direction. When using equal-area map projection, triangular and hexagonal grids produce the least amount of apparent cell shape distortion, although square and rectangular grids provide nearly equal area cells at the spatial scale of most individual countries. Ideally, the starting point of the grid is randomly located and the grid has a random orientation to avoid alignment with anthropogenic features, which tend north-south or east-west in some regions. If plot locations are located at grid intersections or at fixed locations within cells, then knowledge of the grid size and the location of a single plot allows other plots to readily be found, thus creating the potential for land managers to treat plots differently than the surrounding landscape (i.e. treatment bias). Random selection of plot locations within each grid cell meets the assumption of probability sampling and also avoids potential treatment bias, which could be a problem if results-based payments are involved. If the randomly chosen point for a particular grid cell falls outside the population boundary, no sample is taken for that cell, even if most of the cell is within the population. For example, if a cell falls on a coastal area (or at the border of a country) and the selected plot location falls in the ocean (or in the adjacent country), no observations are collected for that cell.

If the NFI plots were distributed using a systematic grid that covered only a subset of the landscape, the same grid spacing can be used to extend the sample into areas that were not originally sampled. For example, if the original sample was constrained to natural forest, as determined from a map, then the sample may be extended to include areas that meet the adopted definition of forest, but occur outside the original map of natural forest.

3.2.1.3 Stratified estimation

NFIs, as well as other sample-based monitoring programs, may use stratification as part of their sampling design. In statistics, stratification subdivides a population into sub-populations, called strata, for two primary purposes:

1. to identify important sub-populations such as primary versus modified natural forest, or deforested versus undisturbed forest area for which separate estimates are required;
2. to reduce the uncertainty (increase the precision) 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. If the primary purpose of stratification is to reduce uncertainty, then population units assigned to the same stratum should be more similar to each other than to units assigned to other strata. An alternative to stratification is to use model-assisted methods which can yield more precise results.

Two approaches to stratification are common. One characterised as stratified sampling and estimation and the other as post-stratified estimation using an equal probability sample. The primary distinction between the two approaches is whether the sampling depends on, or is independent of, the stratification. These two approaches are sometimes referred to as pre-stratification and post-stratification, respectively, although these terms are often misinterpreted. With post-stratified estimation, the sampling is conducted independently of the stratification, either before or after delineation of strata. For both stratified sampling and post-stratified estimation, the strata must completely cover the population, with no overlaps and no gaps, and therefore have known strata weights.

With stratified sampling, the stratification is established before the sampling, primarily so that desired within-strata sample sizes can be ensured, thus the sampling depends on the stratification. The sample sizes can be allocated to the strata using proportional allocation (based on strata areas), Neyman allocation (based on strata variances), or optimally (based on a combination of variance and cost) (Cochran, 1977). For long term monitoring, proportional allocation is typically used and recommended to avoid the complexities of changing probabilities of plot selection (Schreuder *et al.*, 1993). While these are the most common allocation rules, plots can be disproportionately allocated to strata for other reasons. For 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 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). A third example is to determine where to use different plot configurations, such as using one plot configuration in coastal mangrove forests and another in upland forests, albeit with only a single plot configuration within each stratum. The stratified estimators take the form:

Equation 6

$$\widehat{\mu} = \sum_{h=1}^{H} W_h \widehat{\mu}_h$$

with variance that ignores the finite population correction factor due to the small sampling fractions typical in forest inventory applications,

Equation 7

$$\widehat{V}(\widehat{\mu}) = \sum_{h=1}^{H} W_h^2 \frac{\widehat{\sigma}_h^2}{n_h}$$

where

Equation 8

$$\widehat{\mu}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi} \text{ is the estimate of the within-stratum mean}$$

Equation 9

$$\widehat{\sigma}_h^2 = \frac{1}{n_h - 1} \sum_{i=1}^{n_h} (y_{hi} - \widehat{\mu}_h)^2 \text{ is the estimate of the within-stratum variance}$$

$h = 1, \ldots, H$ indexes strata y_{hi} is the observation for i^{th} reference sample unit in the h^{th} stratum, W_h is the stratum weight calculated as the proportion of the population, and n_h is the within-stratum reference sample size.

Even if stratified sampling is not used, stratified estimation can still increase the precision of estimates. This approach, characterised as post-stratification, can be used with data obtained using an equal probability sampling design to create homogeneous post-strata. With post-stratification, the sampling is conducted independently of the stratification, either before or after delineation of strata. An example is an NFI that uses only permanent plots selected with equal probability across the population, thus the sampling design does not change over time. The post-stratified estimator of the mean is the same as for the stratified estimator. However, with post-stratification, within-strata sample sizes cannot be controlled, but are random. The post-stratified variance estimator (Cochran, 1977, eq. 5A.40) accommodates this randomness and takes the form:

Equation 10

$$\widehat{V}(\widehat{\mu}) = \sum_{h=1}^{H} \left[W_h \frac{\widehat{\sigma}_h^2}{n} + (1 - W_h) \frac{\widehat{\sigma}_h^2}{n^2} \right]$$

where n is the overall sample size.

The penalty term for the fact that the sample sizes are random is generally small, especially when strata sample sizes are large enough to mimic the proportional allocation sample sizes (Westfall *et al.*, 2011).

Cochran's (1977) recommendation of no more than 6-8 strata was confirmed by McRoberts *et al.* (2012) and McRoberts *et al.* (2013) for NFI applications. For both stratified sampling and estimation and post-stratification, the strata must be large enough to ensure sufficient within-strata sample sizes. For post-stratification, Cochran (1977) recommends minimum per stratum sample sizes of 20, Särndal *et al.* (1992) recommend minimum per stratum sample sizes of 10-20, and specifically for temperate forest inventories, Westfall *et al.* (2011) recommend at least 20 plots per stratum. If sufficiently large within-strata sample sizes are not obtained, multiple similar smaller strata can be combined into a single larger stratum.

The stratified and post-stratified estimators of the population mean are unbiased in the sense that on average, over all possible samples of the same size obtained using the same sampling design, 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. The stratified and post-stratified variance estimators are different.

Double sampling for stratification in forest monitoring involves sampling in two phases. The first phase typically entails classification of thousands of systematically selected image points (in aerial photography or satellite imagery) into strata and using the classified data to estimate the strata weights (Cochran, 1977, Section 12.2). Operationally, this task is currently accomplished and simplified using geographic information system (GIS) tools, such as **Open Foris Collect Earth Online** and often freely available satellite data. Advantages over using maps (which have known strata weights) are that the image interpretation can use finer resolution imagery and is thus typically more accurate and can be done sooner in the process. A disadvantage is that the strata weights are estimated, rather than known as in the case of maps, which introduces additional variance. The second phase entails sampling from the list of first-phase image points. Stratified sampling in the second phase can be implemented by randomly or systematically selecting from the list of image points within strata using one of the three plot allocation rules. The estimator of the population mean for double sampling is the same as the stratified estimator. However, the variance estimator must accommodate the estimated, rather than known, strata weights. For very large population sizes (numbers of map units), N, and for first-phase sample sizes, n', much less than N, an approximate variance estimator takes the form,

Equation 11

$$\widehat{V}(\widehat{\mu}) \approx \sum_{h=1}^{H} W_h^2 \frac{\widehat{\sigma}_h^2}{n} + \frac{1}{n'} \sum_{h=1}^{H} W_h (\widehat{\mu}_h - \widehat{\mu})^2$$

The second phase of double sampling for stratification can also be implemented using simple random or systematic sampling from the entire list of first-phase image points, not just within strata. The post-stratified estimators are then used for which the estimator of the mean is the same as for the other forms of stratified estimation. The double sampling, post-stratified variance estimator accommodates both the estimated strata weights and the randomness of the within-strata sample sizes and takes the form (Westfall *et al.*, 2019),

Equation 12

$$\widehat{V}(\widehat{\mu}) \approx \sum_{h=1}^{H} \left[W_h \frac{\widehat{\sigma}_h^2}{n} + (1 - W_h) \frac{\widehat{\sigma}_h^2}{n^2} \right] + \frac{1}{n'} \sum_{h=1}^{H} W_h (\widehat{\mu}_h - \widehat{\mu})^2$$

3.2.1.4 Model-assisted estimation

Model-assisted estimation uses a combination of reference observations for sample units selected using a probability sample and predictions for all population units (Särndal *et al.*, 1992). The predictions may be in the form of map unit values for an existing map, map unit values for an existing map that has been calibrated using the reference observations (Næsset *et al.*, 2016), or predictions from a model of the relationship between the response variable of interest and auxiliary variables (McRoberts *et al.*, 2013; Næsset *et al.*, 2011). Assuming that the reference sample observations are acquired using an equal probability sampling design, the estimator of the population mean is formulated as,

Equation 13

$$\widehat{\mu} = \frac{1}{N} \sum_{k=1}^{N} \widehat{y}_k - \frac{1}{n} \sum_{i=1}^{n} (\widehat{y}_i - y_i)$$

where k indexes the population, N is the population size (number of map units), i indexes the reference sample, n is the reference sample size, y_i is a reference sample unit observation, $\hat{y}_k$ and $\hat{y}_i$ are population (map) and sample unit predictions, respectively.

The first term of the estimator is the synthetic estimator of the population mean, while the second term is an estimate of the bias of the synthetic estimator due to systematic map or prediction error.

If the predictions are based on an existing map or an existing model, regardless of whether it was or was not constructed for the area of interest, the estimator is characterised as the model-assisted difference estimator. If the predictions are based on either an existing map recalibrated using reference observations for the area of interest or a model and corresponding map constructed using reference variable and auxiliary variable observations for the area of interest, the estimator is characterised as the model-assisted generalised regression (GREG) estimator. For both forms, the variance estimator for the estimate of the population mean is formulated as,

Equation 14

$$\widehat{V}(\widehat{\mu}) = \frac{n}{n(n-1)} \sum_{i=1}^{n} (\varepsilon_i - \overline{\varepsilon})^2$$

where,

Equation 15

$$\varepsilon_i = y_i - \widehat{y}_i, \quad \overline{\varepsilon} = \frac{1}{n} \sum_{i=1}^{n} \varepsilon_i$$

Although many early examples of the GREG estimator used linear regression models, any prediction technique including nonlinear models and non-parametric techniques such as k-Nearest Neighbours or random forests can be used. Further, although model-assisted estimators have primarily been used for univariate estimation, multivariate prediction techniques such as k-Nearest Neighbours can also be used (McRoberts *et al.*, 2017). In addition, model-assisted estimators can be used with data acquired using stratified, cluster, or other sampling designs, although both the second term of the point estimator and the variance estimator must be modified accordingly. For continuous response variables, and for maps whose resolution is similar to or only moderately coarser than the reference data, model-assisted estimators can produce considerably greater precision than stratified estimators.

Both stratified and model-assisted estimators for purposes of estimating activity data are described in **Section 4.2.3**.

3.2.1.5 Plot configuration

Plot size is generally in the range 0.01 to 1 hectares in NFIs. There is an inventory cost trade-off between spending more time on fewer, larger plots and spending more time traveling to visit a larger number of smaller plots. Larger plots typically lead to lower variance in estimates, but fewer can be collected for a given budget. In countries with poor travel infrastructure, larger plots can be beneficial; typically, if road or river networks are well-developed, smaller plots often lead to plot savings. Compact, large plot sizes can facilitate integration of plot data with remotely sensed data (Rejou-Mechain *et al.*, 2014). Circular plots, as well as single large plots versus clusters of sub-plots, have proved advantageous for remeasurement due to minimisation of the number of boundary trees and consequent edge effects. To reduce the likelihood of missing boundary trees (or erroneously including trees that are just outside the plot), particularly on steep slopes, most countries with circular plot designs have adopted plot radii of less than 20 meters. In addition, using a cluster of sub-plots increases the plot perimeter, and thus increases the chances of errors at the plot margins. However, in some landscape types, subplot separation can have effects similar to those of increasing plot size, with respect to lowering variance, hence the reason that cluster plots have been used in NFIs for decades. There are precision and ground-efficiency trade-offs of subplot size, number of subplots and the distance between them (Yim *et al.*, 2015; Scott, 1993). The use of cluster plots can cause difficulties when stratified designs are chosen because plots might be distributed across multiple strata; a heuristic is typically chosen to deal with this situation by putting the entire plot in a single stratum and assuming that bias is not increased. Because the density of trees decreases as tree size increases, many NFI plot configurations use two or more plot sizes depending on tree diameter, such as small plots for seedlings and saplings, medium plots for small trees (e.g. 10-30 cm in diameter), and large plots for large trees (e.g. >30 cm). In wet tropical forests, a very large plot for the trees >50 cm in diameter may prove efficient because they can contain a large portion of the biomass.

The trade-offs between plot shape (rectangular versus circular) and plot configuration (single larger plots versus clusters of smaller dispersed sub-plots) can be evaluated to find an efficient solution for each country and to assess the effects of generic, non-optimised solutions. The cost and variability differ by country, and maybe even by region within a country (e.g. **Bangladesh**). Tomppo *et al.* (2014) present an example of such an optimisation study that led to a design optimised for overstorey trees. It is often a matter of field work logistics constraints and the previous experience of the inventory practitioners of a region that determine the finer details of plot design; field trials that compare plot designs and data collection quality in different ecosystems should be conducted prior to the final selection. The role of sampling simulations (Räty *et al.*, 2019) in designing improved and cost-efficient NFI has been crucial in many countries (e.g. the Lao Peoples Democratic Republic, Nepal, the United Republic of Tanzania, Viet Nam). For more on plot design, see FAO (2017).

3.2.1.6 Non-response

Non-response in ground data occurs when data for all or part of an NFI plot (as part of a probability sample) cannot be collected and used in estimation for various reasons. Non-response causes can be grouped into four categories:

1. Hazardous conditions (e.g. cliffs, weather, flooding, fires, illegal activities, political instability).
2. Denied access by individuals or groups (e.g. public or private landowners or inhabitants).
3. Administratively restricted areas (e.g. military bases, protected areas, restricted indigenous territories).
4. Logistical difficulties (e.g. remoteness, lost data or loss of funding).

The institution(s) implementing the NFI should plan for the possibility of nonresponse early in the design phase of the NFI and take actions to minimise the likelihood of nonresponse. Technical partners should clearly communicate the rates of nonresponse, characteristics of nonresponse plots and large inaccessible areas to decision makers so that they can make proper inferences about the results. As a general rule, every reasonable effort should be made to measure all plots.

Non-response can be minimised in the field in at least three ways:

1. Make multiple attempts. In the case of bad weather conditions or denied access from landowners, try again later when conditions improve or ownership changes.
2. Work with people. The need to collect information about forest resources is understandable and appealing to many local communities if they are well informed. Sending socialisation crews and requesting local guide help can improve access to many plots.
3. Replace the plot. In some cases, it is possible to get close to the plot but not to access it directly (e.g. if it is located across a steep and densely vegetation gorge). To avoid losing the plot, an alternative plot can be pre-selected in the same stratum. Field crews should not be allowed to choose the plot location. The concern is that crews will avoid difficult plots and will measure easier alternative plots instead, thus biasing the sample away from difficult but accessible terrain.

Statistical options for addressing nonresponse include:

- Plots with partial nonresponse can be accommodated using the Ratio-to-Size estimator (Thompson, 2012). The numerator in the ratio is the sum of the attribute of interest measured on all plots, including partial plots. The denominator is the sum of the area measured (size) on each plot. Thus, the ratio provides an estimate of the mean value per ha for accessible areas. The variance estimator accounts for the fact that both the attribute of interest and the area measured are random variates.

- Assuming that the nonresponse rate is small, and that the set of nonresponse plots can be considered missing completely at random (Rubin, 1987), the nonresponse plots can be removed from the sample and a slightly smaller sample size can be accepted. Alternatively, if the nonresponse plots have common characteristics such as high elevation or private versus public ownership, and a stratum that encompasses the nonresponse plots can be defined and its total area within the population can be estimated, the nonresponse plots can be deleted from the within-stratum sample, and post-stratified estimation can be used.
- Predict missing plot-level attributes, such as biomass per unit area using any of multiple techniques, but with particular attention to multiple imputation (Rubin, 1987; Mc Roberts, 2003). Nearest neighbour techniques are particularly useful and appropriate for this kind of imputation. Caution must be exercised to accommodate the uncertainty associated with the imputations when estimating variances (Mc Roberts, 2003, Eqs. 4-5).
- Two cases of large areas with complete nonresponse are considered: (1) a large contiguous area with complete nonresponse such as indigenous territories or protected areas; and (2) a large non-contiguous area that encompasses the nonresponse plots can be defined by unique landscape, ownership, or remotely sensed features (e.g. high elevation, private versus public ownership), and whose total area within the population of interest can be estimated. These areas can be considered a separate stratum, and a model-based approach to inference using similar data external to the stratum can be used to estimate the stratum mean and its variance (McRoberts *et al.*, 2014). Because model-based inference is not assured to be unbiased, particularly for small sample sizes, the estimator of the stratum mean may be slightly biased, but a small bias is likely to be preferable to the lack of any estimate.

3.2.2 Intensive monitoring sites

Intensive monitoring sites, such as long-term ecosystem research projects and observational research and experimental plots established within a country or region, can provide useful auxiliary data sets for estimating change in carbon density following land-use change. Unlike statistically based forest inventories, intensive monitoring sites generally use purposely selected sites. These intensive research sites typically have a long history of repeated measurements of a common and comprehensive suite of ecological variables relevant for 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 estimate emissions and removals factors or to parameterise models to scale up estimates to regional and national levels. In such cases, consideration and documentation of the range of conditions to which the available data applies relative to the broader population should be made.

These networks of plots commonly consist of a few plots (or sometimes only one) where the focus is on ecosystem functioning and processes. They can be used to facilitate the inclusion of pools which are subject to slow or relatively small changes in carbon dynamics following a change in land management regime, such as soil or debris pools, or emission sources that are difficult to measure routinely, such as fire events. Typical designs of intensive monitoring sites include paired sites and chronosequences, both of which can be used to infer a temporal trend from a study of a set of sites in different spatial positions, sampled once, and at the same time (Filippi *et al.*, 2016). In paired-site studies, sampling is undertaken at the same time from an undisturbed location and an adjacent disturbed location. Paired sites can be effective in investigating the effects of management changes and developing estimates of emissions from activities across a range of pools, but such designs are typically uncommon due to challenges in establishment and control. Chronosequences, by assuming space-for-time substitution, aim to infer temporal dynamics from measurements at sites of different ages but similar land use histories. Chronosequences are particularly useful when investigating post disturbance recovery of systems that take decades to centuries to recover (Walker *et al.*, 2010; De Palma *et al.*, 2018). It can be challenging, however, to identify sites with matching characteristics across a desired temporal distribution, although time series of remotely sensed images could provide support in identifying suitable sites.

To be useful, original data sets (not just means and distributions) should be available, and data collection protocols should be well-documented and include data quality checks. These characteristics are important for transparent reporting and assessment of estimates. For countries without established NFIs, and thus without NFI ground observations, scaling up data from intensive monitoring sites can be problematic, due to the fact that they are collected using a purposive rather than probabilistic sampling design. Therefore, scaling up intensive site monitoring data for national-scale inference and estimation, in the absence of probabilistic NFI data, requires integrating the intensive site data with remotely sensed data and use of model-based inferential methods.

Intensive monitoring sites can be part of the ground data referred to in the decision tree in **Section 4.4** (**Figure 20**). To be useful, data collection at these sites should be harmonised, as described in the notes for Decision Point 3 in **Figure 20** and also expanded in **Section 4.1.2**. These data 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 remotely sensed data. Data collection and analysis are combined across multiple spatial and temporal scales, with intensive and detailed studies providing specific information to scale-up using remote-sensing techniques, extensive forest inventories and empirical and process modelling (Birdsey *et al.*, 2013).

3.2.3 Other ground data sources

Other useful sources of auxiliary ground data may exist, in addition to those directly collected by a **National Forest Inventory** or from **intensive monitoring sites**. These additional data sources may include disturbance histories, land tenure, forest management plans, harvest statistics, fire area data, fuelwood extraction data (or rate of wood energy for cooking), forest health surveys and pest impact data. They can also include land characteristics such as climate, soil type, elevation and slope. Because the spatial resolution of such data sources varies from relatively fine-scaled, spatially continuous gridded data sets (e.g. elevation) to a lumped characterisation of a single large area (e.g. area burned in an entire country) issues related to harmonisation should be considered (**Section 4.1**).

For countries that have not yet begun assembling such data sets for REDD+ purposes, it can be useful to determine agencies or ministries that may collect or generate these (e.g. a soil survey). In the absence of country specific data, additional data sets can come from neighbouring countries with similar forest types. Relevant regional data can also be useful in the absence of national data. For substantial sources and sinks, the collection of country-specific data should be prioritised.

Because additional ground data sources vary among, and sometimes within, countries, there is no prescriptive guidance on how to integrate them for estimating emissions and removals. Additional ground data, including data based on interpretation of fine resolution imagery, can play an important auxiliary role in estimating emissions and removals from REDD+ activities by providing context for detected (or predicted) changes (see **Box 28**). Sometimes, data from a non-probability sample may also be available and such data can sometimes be usefully combined with a probability sample to enhance analyses (Stehman *et al.*, 2018). Ground data collected at spatially known locations can also be used to calibrate or validate maps based on remotely sensed data, although data used for validation should be on a probability sample.

Box 28: Example of the use of other ground data sources

A common example of the utility of data sets other than NFI or intensive monitoring data relates to logging, which could indicate deforestation, forest degradation, or be part of sustainable forest management activities. In this case, additional ground data on the existence of sustainable forest management plans, the extent of their application and the location of concessions could help with interpretation.

Use of data from other sources for estimating emissions and removals factors and constructing models

National ground data sets other than NFI data may be useful in estimating emissions and removals factors for soil carbon, litter, and deadwood pools through models (**Section 2.4**). The data sets that are most likely to be useful in this regard include data pertaining to harvest rates, forest management plans, plans for road and other infrastructure, use of fuelwood for energy in local communities, and fire statistics.

National (and jurisdictional) data sets 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. Such models allow for more frequent data estimates that may not be collected from NFI cycles. They may also be more representative than estimates derived from intensive monitoring sites.

Use of data from other sources for REDD+ estimation

Combining activity data (areas of deforestation, afforestation/reforestation, forest degradation, improved forest management, areas undergoing carbon stock enhancement) with ground data can inform the estimation of ground conditions and the likelihood of future changes within these areas. Such ground data could include, but are not limited to, 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. Statistical models that classify the risk of disturbance utilising such additional data are available (see **Geomod/IDRISI**, **Land Change Modeler**, **Dinamica**). Alternatively, countries can develop their own data which are typically linked to Tier 3 integration frameworks (**Section 2.4**).

For the purpose of assessing deforestation and degradation, all additional data sources 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. Predicting the locations of potential deforestation or degradation can be a cost-effective way to target early warning monitoring and the strategic use of fine resolution imagery.

3.2.4 Considerations for using existing data

Many countries have a variety of existing data sets that may be useful in establishing estimates. When assessing if existing data sets can support the defined goals and objectives of the NFMS, the following considerations can help to maximise the utility of existing data or to determine whether the establishment of a new data collection framework is warranted.

National Forest Inventories

- After clearly defining the information needs, precision requirements and cost constraints, determine whether the existing NFI meets these needs. If the data collected use different definitions or standards, then it may be challenging to use them. However, if the data are useful but some attributes are missing, then attributes can be added to the inventory. If greater precision is required, then plots can be added. However, often greater precision is desired than funding allows, so some trade-offs will be required. These can be partly addressed by the choice of sampling and plot designs (**Section 3.2.1**).
- Determine whether the existing NFI uses a probabilistic sample to enable design-based statistical inference and credibility, where all areas within the population have a positive and known probability of selection. Also, consider whether plots have been treated differently from the surrounding landscape due to visible markings of the plot location which can lead to treatment bias. Often, an inventory design uses a probabilistic sample, but the data actually collected do not represent a realisation of that design, and thus cannot be considered as having come from a probabilistic sample. For example, in some inventories plots that fell in non-forest land were inappropriately moved to forest land, and inaccessible plots occur in most inventories and result in nonresponse. No inventory is perfect, so gradations of applicability of NFI data should be considered. Also, consider whether plots have been treated differently from the surrounding landscape due to visible markings of the plot location, which can lead to treatment bias.
- Determine whether the existing NFI samples all lands, or at least all that are forest or could become forest. This requires a clear, operational definition of forest and other land classes. If only the forested portion of the map was sampled, then any forest areas occurring in non-forest portions of the map have no probability of selection, since all maps have some classification error. Due to this and the fact than non-forest land can become forest over time (afforestation), ideally all lands are included in the sampling frame. If inland and coastal waters are well-mapped and stable over time, then water can be taken out of the sample. Otherwise, include water in the sample, thus allowing for estimates of the proportion of forest, water and other non-forest land and change in them over time. For plots that did not meet the operational definition of forest and therefore were not measured using NFI protocols, were the land use and cover characteristics assessed? If so, for any plots that change to or from forest, associating their previous or subsequent land use and cover can help to identify drivers of change. In countries where trees outside forest are an important part of the tree resource, were trees, soils and other attributes measured?
- Consider benefits and long-term implications of stratified sampling and estimation and post-stratified estimation (**Section 3.2.1.3**). For monitoring, a drawback of using different sampling intensities by stratum is that strata boundaries can change over time, so optimal allocation at time 1 may be suboptimal in the future.
- Consider how the NFI handles unmanaged or various kinds of difficult to access areas.
- Determine whether plots can be relocated, since permanent plots are best for estimating change and therefore Emission Factors. Good plot markings allow the next crew to find the plot, but they

should be largely invisible to the untrained eye (to avoid treatment bias). If existing plots cannot be reliably relocated, they may need to be replaced. If a small portion of the plots are lost, then a new plot can be placed at the original coordinates. Otherwise, a whole new inventory may be necessary, but this results in a substantial loss of information on change.

- A **Quality assurance and quality control (QA/QC)** program is crucial to achieving good data.

If the current NFI data do not meet one or more of these characteristics, consider whether to modify the existing NFI or establish a new one. Before abandoning an existing NFI, recognise that the ability to estimate change using the existing data would be lost, and that it would take two measurement cycles of the new NFI to be able to estimate change. As a means of transitioning from one NFI design to another, the methods in Köhl *et al.* (2015) could be applied.

Intensive Monitoring and Research Sites

- Intensively monitored sites located to include the range of forest types and conditions that occur within the country are preferred. Such sites can also be useful where they are representative of a limited range of conditions that are consistent with MRV objectives and can support country-specific improvements (e.g. from Tier 1 to Tier 2) to estimation methods of carbon pools, forest ecosystems, IPCC land-use change classes, or REDD+ activities.
- Where plots are located for atmospheric monitoring (flux) towers, ideally these would be selected in a systematic fashion surrounding the tower and at distances likely to affect the readings at the tower.

For experimental plots, ideally the plots are distributed among mapped classes of forest types, stage of development classes, and other factors such as topography, soils, and elevation, which affect current stand conditions and the likely responses to experimental treatments. Within the resulting classes, the ideal would be to randomly select sample plot locations to collect new data.

All Ground Data Sources

While many ground data sources are available, the quality of those data is often not easily determined. Assessment of potential data sets against the following questions may assist in identifying useful data that are fit the purpose:

- Are quality assurance reports available? If not, consider asking other users for their assessment of the data (e.g. expert judgement)?
- Are the data collected on a cycle that can support repeated MRV commitment timelines?
- Are the data available for the areas of interest, ideally the entire country?
- Are the data of the appropriate spatial resolution and can the data be assigned (attributed) to individual plots, strata or other relevant aspects of the NFMS?

For other aspects of ground sampling, see **Appendix A**.

Chapter 4 Data Processing

This chapter addresses requirements for estimating activity data and emissions and removals factors. Statistical inference for area and uncertainty estimation using unbiased estimators that comply with the IPCC Good Practice Guidelines are illustrated. Methods for combining uncertainties to estimate overall uncertainty are provided, building on IPCC guidance. Guiding principles given at the end of the chapter summarise aspects that can help a country to select a particular combination of data sources and methods to support reporting on GHG emissions and removals.

4.1 Combining data from different sources

Because probability samples of ground observations are seldom, if ever, available in sufficient quantity and kind, at acceptable costs, estimation of emissions and removals must rely on data from multiple sources. Even with large, probability-based, ground sample sizes, auxiliary remotely sensed data are well-documented as a source of information for increasing the precision of estimates. Further, auxiliary data from multiple sources may produce greater beneficial effects than data from a single auxiliary source. For example, data from logging, fire, land tenure and related sources can be used to **attribute** drivers. Thus, even under otherwise favourable conditions, issues related to combining data from different sources are relevant.

When sufficient probability samples of ground data are not available, relevant data from alternative and/or multiple sources become not just desirable, but necessary. Remotely sensed examples include replacing data for cloud cover and completing time series with missing data. For all particular situations, multiple common issues must be addressed, including:

- data from all sources must be spatially-explicit in the sense that they are associated with known ground locations or with identified boundaries;
- when available, data of greater quality relative to factors such as resolution, timeliness and uncertainty should be used in lieu of data of lesser quality;(135) and
- data from all sources must be harmonised to circumvent and/or accommodate factors such as different spatial resolutions, different observation and measurement protocols, and different temporal associations.

4.1.1 Combining ground observations from different sources

Challenges associated with combining ground observations from different sources(136) are primarily associated with estimating emissions and removal factors for the gain-loss approach. All efforts to combine data from different sources assume that all data are geo-referenced to the same coordinate system.

For estimation and modelling problems, an underlying assumption is that observations or measurements of the response or dependent variable have been acquired using the same protocols related to factors such as sampling design, plot size, minimum tree diameter, minimum area and crown cover in the definition of forest, and time since observation or measurement. Failure to use

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(135) Where data of greater quality are not available and lesser quality is used, it may not be possible to separate uncertainty due to the process from uncertainty due to the lesser quality data.

(136) Likely characterised by different observation and/or measurement protocols and different sampling designs.

the same protocols induces data incompatibilities and uncertainties into estimates. For example, different minimum diameters mean that two otherwise identical plots would have different estimates of plot-level biomass, or different plot sizes could mean different relationships between plot-level biomass and spectral values for pixels of remotely sensed optical data containing the plot centres. However, for many tropical situations, data characterised by these incompatibilities may be the only data available. The challenge is then twofold: first, to determine which of these incompatibilities are actually problematic, and second, to determine either how to harmonise the data to eliminate the incompatibilities, or to compensate for their effects in the analysis.

IPCC good practice requires that estimators are unbiased, at least to the degree possible, and that uncertainties associated with the estimates are themselves estimated and reported. For all practical purposes, this means that two samples of ground conditions for two dates are required where the observations for the two samples may or may not be for the same plots. The multiple observations and measurements over time from long term research plots may be well-suited for estimating emissions and removals factors. However, consideration must be given to whether plot conditions and attributes correspond with the features of the activities of interest, for example, forest-remaining-forest or thinning treatments as a form of degradation.

When a comprehensive, consistent sample for a date is not possible, data from multiple sources must be aggregated. An issue of concern arises when the sampling designs associated with the different data sources differ substantially, such as with respect to sampling intensity, geographical distribution, and environmental conditions. For example, a set of research plots may cover only a small geographical area, whereas a set of pre-harvest commercial plots may be for only a few select species. Multiple approaches for accommodating such differences may be considered. First, if all the sources are associated with probabilistic sampling designs, then a stratified approach could be considered in which the regions associated with the same sampling designs are considered strata. Second, if regions associated with the different sources overlap, separate estimates can be combined by weighting individual estimates inversely to their variances. Third, if the plots in totality cover most of the activity area of interest, an ad hoc approach would be to overlay the ground distribution of plots with a regular polygonal tessellation and randomly select one plot in each polygon (Brand *et al.*, 2000). Some ground sampling may be necessary to acquire data for polygons with no plots as a means of obtaining coverage of the range of conditions. Finally, if a model of the relationship between a response variable such as biomass and remotely sensed auxiliary data can be constructed, then model-based inference which does not require probability sampling may be necessary. However, for model-based inference, an underlying assumption is that the distribution of the auxiliary variable for the combined sample data is similar to the distribution of the entire population. Of importance, model-based inference is not necessarily unbiased, particularly when the two distributions differ substantially.

If protocol thresholds such as plot size or radius and/or minimum diameter are demonstrably different, then some form of data harmonisation is necessary. For modelling applications, multiple studies have shown the advantages of larger plots with smaller area to perimeter ratios that minimise edge effects (Mauya *et al.*, 2015; Næsset *et al.*, 2015; Tomppo *et al.*, 2017). However, no studies evaluating the effects of constructing models using data for mixtures of small and large plots are known. Nevertheless, because smaller plots tend to have more extreme per unit area observations than larger plots, the effects are expected to be a form of heteroscedasticity and model parameter estimates that produce predictions skewed toward the data for the smaller plots. Both conditions could be at least partially addressed by weighting plot observations by plot size. Alternatively, if within-plot locations of individual trees are available, harmonisation could be accomplished by applying the smallest plot radius or area to all plots.

Cienciala *et al.* (2008) reported a 26 percent difference in the carbon sink estimate for a Nordic country depending on the minimum tree diameter used. Harmonisation with respect to this effect may entail use of the greatest of the minimum diameters among the multiple sources. Finally, to harmonise plot data relative to observation/measurement date, growth and/or mortality, models may be necessary to predict current conditions on plots that were measured in the past. However, consideration must be given to the additional uncertainty in estimates accruing from the uncertainty in the model predictions.

The issue of harmonisation of national forest inventories in Europe has received considerable attention, including development of useful harmonisation methods. Although developed for temperate forests, these methods are likely to also be applicable for tropical forests (McRoberts *et al.*, 2009; Tomppo *et al.*, 2010).

4.1.2 Combining remotely sensed data from different sources

Remotely sensed data from multiple sources are combined for two primary purposes:

1. to support general estimation; and
2. to compensate for missing data.

Examples of the first purpose include use of interpreted fine resolution imagery as reference data in conjunction with medium resolution Landsat-based activity class maps as auxiliary data. In addition, biomass and other forest attribute maps constructed using combinations of LiDAR, radar and optical data, typically all of different spatial resolutions, are used as auxiliary data with stratified and model-assisted estimators of emissions and removals factors with the gain-loss method and of emissions and removals with the stock-difference method. An example of the second purpose is use of coarser resolution MODIS imagery to fill finer resolution Landsat cloud cover gaps and scan line correction errors.

Rapid advances in remote sensing technology have increased data availability. New data sets from these sensors may bring spatial and temporal benefits to replace or augment historical data sets and improve estimates. Often the most important factor when combining remotely sensed data from different sources is dealing with the inevitable differences in spatial resolution. Solutions include using the same value of a coarser resolution pixel for all associated finer resolution pixels and resampling coarser resolution data to finer resolution. For estimating activity data, the interpreted fine resolution imagery serve as the reference data.

From the perspective of activity data, Sentinel-2 and Landsat are the two most relevant satellite systems. The National Aeronautics and Space Administration (NASA) is currently in the process of creating a harmonised surface reflectance product (HLS),(137) based on the combination of Landsat and Sentinel-2 data (Claverie *et al.*, 2018). However, using these data could lead to inconsistencies in the time series. Such inconsistencies can be addressed using the same techniques that address recalculation in complex scenarios as indicated in **Section 2.3.8**.(138) Where bias caused by the inconsistency remains, it should be assessed and the error removed to the extent practical. Once all practical efforts have been made to remove the bias, further action can be taken when using this estimate in an accounting context (such as a results-based framework to reward REDD+ efforts (**Box 38**).

One common example of possible inconsistencies caused by using more advanced data sets is when augmenting the baseline data with different data from a new remote sensor. For example, if Landsat data were used exclusively for estimating the reference level, and then Sentinel-2 data is added to the Landsat data, using the HLS product for example, for map-making and/or for collecting reference

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(137) HLS data are currently available for North America and globally distributed test sites but global HLS data are planned. The HLS data are downloadable at **https://hls.gsfc.nasa.gov/**.

(138) See **Volume 1, Chapter 5, of the 2019 Refinement** (IPCC, 2019).

observations. This change in data could potentially produce different (i.e. better) results than if using Landsat alone. A comparative analysis of such differences should allow to identify and remove the biases to the extent practical, if any.

4.1.3 Combining ground and remotely sensed data

Ground and remotely sensed data are combined for multiple purposes including to:

- calibrate and evaluate the accuracy of a classifier;
- construct models that serve as the basis for constructing biomass maps;
- assign points for image interpretation to strata based on activity map classes;
- assign plots to strata for stratified estimation of biomass; and
- estimate model-assisted means and variances.

Typically, field plots are associated with sensor footprints that contain the plot centres. If the plot is considerably smaller than the sensor's footprint, then it is reasonable to ask the degree to which the sensor values correspond to the plot data. Although correlations between data for homogeneous plots even as small as 170 m^2 and 30 m x 30 m Landsat band values are often fairly large, particularly for categorical response variables, the correlations may deteriorate rapidly for plots split among multiple classes of the response variable and when plots straddle pixel boundaries. Although image interpretations are not ground observations, they can serve as reference data in a manner similar to ground observations. Thus, similar caution must be exercised when interpreted points or pixels from fine resolution imagery are used to validate the class value for a 30 m x 30 m Landsat-based activity map unit. In particular, the interpreter must interpret the entire extent of the activity map unit, not just a single point or finer image pixel.

Plots consisting of clusters of dispersed subplots present unique challenges because the spatial extent of a single plot cluster is typically much greater than the size of a single remote sensor footprint or single map unit. For training a classifier or constructing a model, there are two options. First, individual subplots can be associated with sensor footprints, but the analysis must then accommodate the expected large correlations among observations of the response variable for subplots of the same plot. Second, data for the entire plot or plot cluster can be associated with a block of pixels or map units that encompasses the entire plot or, for LiDAR data, metrics can be calculated for a footprint that circumscribes all the subplots. Difficulties also arise when using stratified estimators with plot clusters. Inevitably, some plots within the same cluster or subplots of the same plot will straddle stratum boundaries and, therefore, will be assigned to different strata, thereby violating the principle that a plot is assigned to one and only one stratum. Although the analysis could be based on the assignment of individual plots within clusters or subplots within plots, an adverse consequence would be that estimates of means for different strata might not be independent. Caution should therefore be exercised when selecting plot configurations that feature distances between individual plot components that are less than the range of spatial correlation.

For LiDAR applications for which metrics correspond to plot boundaries, edge effects become important. In particular, because the biomass of an entire tree is assigned to the location of the tree stem centre, trees with centres near but inside the plot perimeter may have branches extending outside the plot. The effect is to overestimate the biomass associated with the LiDAR metrics. Similarly, trees with centres near but outside the plot perimeter may have branches extending inside the plot perimeter, thereby underestimating the biomass associated with the LiDAR metrics (Næsset *et al.*, 2015). This effect is exacerbated for tropical forests with large trees (Mauya *et al.*, 2015) and for plot configurations with large perimeter to area ratios such as rectangular plots and plots configured as clusters of subplots. The effect is less severe when the plot is wholly contained within large optical image pixels.

Finally, geo-referencing of plots and remotely sensed data to the same coordinate system is important. The effects of inaccurate geo-referencing of plots relative to any spatial data including images, LiDAR metrics or maps are to cause mismatches between the plot data and the spatial data. For stratification, the effect is to cause plots to be assigned to incorrect strata, thereby introducing bias into the stratified estimator and increasing the stratified variance estimate. For modelling applications, the effect is to cause uncertainty in the predictor variables, a condition characterised as errors-in-variables (Carroll *et al.*, 2006; Fuller, 1987), and introduce bias into estimators of model parameters and, thereby, into model-assisted and model-based point estimators. For a combination of NFI plot forest/nonforest data and Landsat data, McRoberts (2010) reported that the effects of geo-referencing errors were increased deviations in estimates of forest area with greater forest fragmentation. In addition, standard errors were underestimated.

For LiDAR applications in temperate and boreal forests, McRoberts *et al.* (2018c) concluded from the recent literature that for circular plots with radii greater than 10 m and geo-reference errors less than 5m, the effects were minimal. McRoberts *et al.* (2018c) compared the effects of GPS receivers with 5-10 m accuracies and receivers with sub-meter accuracies on estimates of mean aboveground biomass per unit area. T he results indicated little differences in estimates of means, but that standard errors were slightly greater for the less accurate receivers.

Overall, the effects of geo-referencing errors on estimators depend on forest structure and forest fragmentation, are smaller for larger plots, tend to increase the bias of point estimators, and typically increase the uncertainty of estimates.

4.2 Methods for estimating Activity Data

Activity data can be estimated using sample data or sample data combined with maps. Though sample data alone are sufficient to estimate activity data with confidence intervals, the inclusion of maps to estimate activity data serves multiple purposes. First, maps can serve as the basis for stratification, either before or after establishing and interpreting a sample unit. Maps depicting forest classes, and particularly forest change classes, can be used to support construction of stratified sampling designs or post-stratification analysis for the purposes of estimating activity data with greater overall precision than sample data alone. Second, maps of continuous variables, such as percent forest canopy cover and even biomass, can be used directly with model-assisted estimators to estimate rates of forest change and can be aggregated to produce forest class maps. Third, maps are useful for depicting the general spatial distribution of land attributes in general and forest resources in particular, which can be especially useful for land management. It is important to remember, however, that pixel counts from maps alone should not be used to estimate activity data. Factors that influence a country's decisions concerning which data and methods to use for estimating 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 the general level of technological capacity.

4.2.1 Maps generated from remotely sensed data

Maps are important components in a National Forest Monitoring System. Methods for constructing maps of categorical variables from remotely sensed observations are referred to as image classification, and there is a long history of their use. There has also been extensive research on the most accurate 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) Classification can be done by visual interpretation, but this can be highly human resource intensive(140) because the number of pixels may be very large and interpretations can vary due to human judgement. With the opening of the Landsat archive in 2008 and the free data policies of Landsat and Sentinel-2, algorithms that make use of time series of satellite data have been developed. Algorithms that enable time series-based approaches to change data generation enable a more comprehensive assessment of the land surface (**Box 30**). A time series-based algorithm often requires a substantial amount of computing power and data storage, but such bottlenecks have been mitigated by cloud computing platforms, allowing users to execute algorithms(141) on a dense time series of satellite data without having to download the data.

Regardless of the classification approach and algorithm, the first attempt at image classification may not 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. It is common practice to manually change the values of misclassified pixels, know as a map clean-up. Users incorporating maps into their activity data estimation procedure are free to improve their maps through these and other approaches such that, when final area estimates are calculated, the mapped strata represent as accurately as possible the actual earth surface conditions for the time periods being considered.

Attribution often integrates remotely sensed data, forest inventory and auxiliary data sets 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 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 other techniques (e.g. **attribution**) (Kennedy *et al.*, 2014).

As explained in **Section 4.2.3**, activity data should not be estimated by *pixel-counting* in maps but by sampling-based methods to satisfy the IPCC criteria of good practice. Maps often serve the important role of stratifying the study area in sampling-based approaches, and as such can help to reduce the

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(139) Packages include **Orfeo**, **QGIS**, **Open Foris** and **GDAL**

(140) See Section 2.1 of the **GOFC-GOLD Sourcebook**

(141) Popular algorithms include LandTrendr (Kennedy *et al.*, 2014), CCDC (Zhu and Woodcock, 2014a), CODED (Bullock *et al.*, 2018) and BFAST (Verbesselt *et al.*, 2010).

uncertainty in activity data estimates.

Box 29: Pixel and object-based methods and segmentation

Maps of land cover and land-cover change can be produced 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 these can sometimes yield higher overall accuracy than pixel-based methods for land cover classification (Gao and 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 and JRC, 2012). Tracking change at the pixel level opens the way to better representation of carbon pool dynamics, though 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 (e.g. 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.

In addition to the general principles of consistent representation of land, MGD advice is that:

- Once a pixel is included, 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 paid 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.

4.2.2 Monitoring of changes and disturbances on the land surface

Change detection is one of the most common uses of remotely sensed observations, 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, there are two important characteristics to change detection for the purposes of monitoring land-use change; i) time series and ii) attribution.

At least two dates of images (end-points) are necessary to map change; however, identification of permanent land-use changes may require more data and analysis. Change detection methods that are based on i mage classification commonly use multiple images to make the assignment to stable classes (places that have not changed), as well as change classes, such as Forest Land 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 Strahlers, 1994). The GOFC-GOLD Sourcebook (GOFC-GOLD, 2015) includes descriptions and examples of several change detection methods.

In recent years, such traditional change detection methods have become less popular in the literature as methods that use many images, or a time series of observations, have increasingly been used (Chen *et al.*, 2004; Kennedy *et al.*, 2007; Verbesselt *et al.*, 2010; Zhu and Woodcock, 2014a; Bullock *et al.*, 2018; Fortin *et al.*, 2020). The term time series in a remote sensing context typically refers to a time series of observations of the same location acquired from a remote sensing instrument.(142) Time series-based approaches have many advantages, as they are not so dependent on the conditions at the time the individual images were collected. Analysis of time series data enables the monitoring of more subtle changes in ecosystem health and condition related to land use dynamics, and hence, shifts the analysis away from traditional change detection using two points in time, to continuous monitoring of the land surface (Woodcock *et al.*, 2020). Because of the increased ability to monitor the fate of post-disturbance landscapes with time series-based approaches, advances have been made in recent years related to the monitoring of forest degradation. Forest degradation is often spectrally subtle and spatially isolated, which complicates its detection in remotely sensed data. Further complicating the issue is the often smaller spatial scale at which degradation events occur, scales smaller than that of easily available remotely sensed data. Fine resolution data has been used to detect forest degradation (e.g. Rahm *et al.*, 2013), but the cost of acquiring multiple images over the same area and issues related to cloud screening, geometric registration and varying view angles, makes automated routine and consistent monitoring difficult, if not impossible (Goetz *et al.*, 2015). Instead, frequent acquisition of observations of the same place is needed.

Degradation can be a gradual process in which biomass is continuously removed over longer periods in time, or the result of rather abrupt vegetation damage caused by, for example, selective logging. Time series-based methods alleviate many of the issues of degradation mapping using single fine resolution images. Examples of continuous monitoring of forest degradation using time series of satellite data have started to appear in the literature (Bullock *et al.*, 2018; Bullock *et al.*, 2020). Still, algorithms that operate on dense time series of satellite data provide a more complete assessment of landscape dynamics (Kennedy *et al.*, 2014) but have yet to make a marked impact in many tropical regions where they are needed the most. The demands of downloading, storing, pre-processing and processing data have prevented implementation outside a few selected research groups. That situation is changing as cloud computing platforms such as Google Earth Engine (Gorelick *et al.*, 2017) provide direct access to the satellite data and to several time series-based algorithms. For example, the CCDC, CODED, LandTrendr and BFAST algorithms are available in Google Earth Engine. **Box 30** presents more detail

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(142) Most time series-based approaches in the literature use data from the Landsat satellites (Woodcock *et al.*, 2020).

on the utility of dense time series in land-use classification.

Of importance to the monitoring of change(143) is the process of **attribution**, which associates observed land cover and land-cover changes with land use and land-use change (IPCC, 2019). Attribution facilitates neither over- nor underestimating emissions from these lands by:

- determining if a change in forestland is temporary (e.g. a disturbance from sustainable logging), permanent (e.g. conversion to agricultural land or settlement), or the result of natural disturbance (e.g. cyclone); and
- assigning disturbance types to forest strata to enable representative methods for estimating emissions and removals to be applied.

Understanding the causes and drivers of natural and human-induced forest cover change and the subsequent forest recovery and succession dynamics enable the estimation of the impacts on carbon stock changes and the associated greenhouse gas emission (Spalding, 2009; Kurz, 2010; Masek *et al.*, 2011; Schroeder *et al.*, 2011). For example, land clearing with or without fire is associated with differences in the amounts, timing and composition of CO_2 and non-CO_2 GHG emissions.

Attribution relies on the combination of auxiliary data sets (**Box 31**) to develop rules to estimate the likely disturbances that caused the observed land-cover changes based on their spatially-explicit location. Data sets that can be used for attribution include data on fire, cyclone trajectories, forest management boundaries, and information on clearing for agricultural activity. These data can include national statistics collected by relevant national agencies, and may be:

- spatially-explicit: where disturbance events contain information about their exact location in space; or
- spatially-referenced: where the year and number of disturbances are recorded, but not their detailed spatial location (e.g. summaries at municipality level).

Determining the fate of the post-disturbance landscape is not a simple task, particularly where change tends to be gradual and slow relative to the initial disturbance or change event. Needless to say, with repeated observations of the post-disturbance area, the ability to attribute the change to a driver greatly increases compared with a traditional change detection analysis.(144) Decreasing the time interval between time series observations leads to continuous monitoring of the landscape, as opposed to simply detecting change. This shift towards monitoring is advantageous as it advances the ability to determine the drivers and timing of change (Woodcock *et al.*, 2020) which can in turn facilitate increased accuracy of emissions estimation.(145)

Box 30: 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

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(143) In particular, REDD+ activities and conversion between IPCC categories.

(144) Relying on the difference between two points in time.

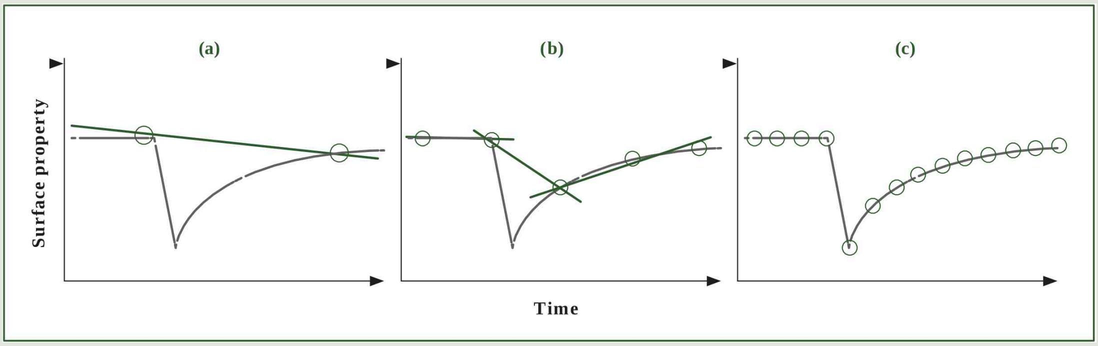
(145) Arévalo *et al.* (2020) presents a good example of how a time series-based approach enabled post-disturbance monitoring and change attribution in a tropical forest landscape.

series as a whole.

It is useful to distinguish between two or a few images over a study period (e.g. 10 to 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 due to 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 to 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 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 characterisation 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 **Figure 18** only two observations in time are available in (a) and five in (b), whereas a dense time series is available in (c) that allows for an accurate representation of the activity.

Figure 18: Tracking activities is possible with a dense time series of land cover observations



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 characterise 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 of carbon sequestered in the recovering forest and soil following the logging event. See **Section 2.4.2** for examples of operational systems that use this method.

To achieve the results illustrated in **Figure 18**, it is possible to create pixel-level composites by applying a statistic (e.g. median or max value for example) to a fixed number of observations, select the best images according to some criterion (e.g. growing season, minimum cloud cover, etc.), or try to use all the 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 with 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 have been used for making global maps of tree cover change on an 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 intervals (Kim *et al.*, 2014). The latter has the advantage of a reduction in data volume, which allows algorithms to process the data faster, 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.

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 and Woodcock, 2014a), BFAST (Verbesselt *et al.*, 2010; Verbesselt *et al.*, 2012; DeVries *et al.*, 2015), and CODED (Bullock *et al.*, 2018) are examples of change detection algorithms that analyse all available observations. The approach is more computationally intensive and requires detailed screening for clouds and cloud shadows. 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 data other than Landsat will most likely 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 due to 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, which are available free of charge. Although both CCDC (Xin *et al.*, 2013) and BFAST (Verbesselt *et al.*, 2012) 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**, **AREA2** and **Collect Earth Online**, the collection of temporal reference observations is possible. When working with more advanced time series-based algorithms, it is important to keep in mind that the output is often a map or several maps that should not be treated differently from other maps.

Box 31: Example of data used and rules applied to attribute fire and hurricanes to land-cover change in Mexico

National statistics of wildfire information in Mexico have been recorded since 1970 for each state in tabular form in a national database maintained by the National Forestry Commission of Mexico (CONAFOR). Historical records include the number of fires and total hectares burned per year, aggregated by state. From 2005 onwards, the database has included additional information: spatial coordinates of the fire central ignition point, cause of ignition, number of hectares burned, and type of ecosystem affected (temperate, tropical, arid) by municipality. Spatial layers are also available from the same database, from 2005 onwards, containing the spatial coordinates of the central ignition point, but not the polygon of the area burned. However, 39 percent of the fire plots in tabular form (mostly from 2005, 2006, and 2009) did not include geographical coordinates, and were not contained in these layers. These fires accounted for approximately 25 percent of the total area burned over the period. As it is not possible to link the non-spatial fire events with the spatially-explicit land-cover change information, only spatial data sets of the fire points with coordinates were used. Annual fire maps were then generated by buffering the ignition points with an area equal to the number of hectares burned per fire.

Information on the trajectories of tropical hurricanes that crossed the region from 2005 to 2010 was available from the National Climatic Data Center (NCDC, 2012). For each hurricane, tabular data on the date, points of landfall, pressure, date, and wind speed for each storm were available. To assess the potential impact of the hurricanes beyond the storm trajectory, tracks are buffered according to the disturbance severity associated with the Saffir-Simpson category (NHC, 2013). To do so, buffer distances were derived from Skwira *et al.* (2005). rain-band width studies, with 15 km for major impact hurricanes categories (category IV or V), 10 km for category III and II, and 5 km for the remaining lower-impact storms.

Annual agricultural activity maps were generated using data from the Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food of Mexico known as SIACON (SAGARPA, 2012). This program provides tabular data on the total area of annual cultivated land by state and municipality. Since the database lacked spatially-explicit information, the cultivated area was referenced to the INEGI municipality polygon. Additional data on agriculture were retrieved from the Mexican National Statistical and Mapping Agency (INEGI, 2003) land use and vegetation series developed for 2003 and 2007 (INEGI, 2007).

These data sets were used to differentiate permanent cultivation areas from the rest of the agricultural activities. A mask was generated locating areas that fell under the status of permanent cultivation and 100 percent impact was assigned to them. Carbon budget models were then parameterised to represent these areas with a constant 100 percent impact and simulate no forest regrowth. Areas of permanent cultivation were masked and annual maps produced by subtracting the hectares identified under permanent cultivation by municipality from: (1) the cultivated hectares reported annually by municipality in the SIACON program; and (2) the area of the municipality. The degree of impact was expressed as the percentage of total cultivated area by municipality.

Source: Adapted from Mascorro *et al.*, 2015

4.2.3 Estimating area, area change and their uncertainties

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).

The latter criterion presumes that uncertainties are estimated, and that they are estimated correctly.

In statistical terms(146), 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 characterised as unbiased if the average of all estimates calculated using data for all possible samples of the same size acquired using the sampling design equals the true value of the parameter of interest; otherwise, an estimator is characterised 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 a confidence interval. A confidence interval expresses the uncertainty of an 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 percent 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.

Approaches that produce estimates of activity data from remotely sensed data must also be capable of accommodating the effects of map classification errors and reporting confidence intervals. 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 should be avoided because it provides no assurance that estimates are neither over- nor underestimates or that uncertainties are reduced as far as practicable.

Area estimates that meet the IPCC good practice criteria must then come from a sample of the overall study area in which we can say that the interpretations at each sample unit represent the true land cover/land use on the Earth's surface at the desired date of analysis. These *true* sample interpretations are referred to as reference data. Reference data, thus, are the source of information used to estimate activity data, and a map, of an activity and/or of change, serves to guide sampling to acquire reference data more efficiently and as auxiliary data to increase the precision of activity data estimates. The most reliable source of reference data are often considered to come from direct observations of ground conditions by trained field crews. However, due to the expense and effort associated with gathering high-quality field data, visual interpretation of satellite or aerial imagery is often used in place of field-based observations as reference data. 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 remotely sensed map data (Olofsson *et al.*, 2014).

For accuracy assessment and area 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 construct an activity or land-use change map are collected. Probability sampling designs to consider are **simple random (SRS),**

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(146) A comprehensive list of statistical terminology is **available here**

systematic (SYS), **stratified random**, (simple random or systematic sampling within strata), 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 frequency of occurrence in the population. 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 multiple 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 geographical 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.

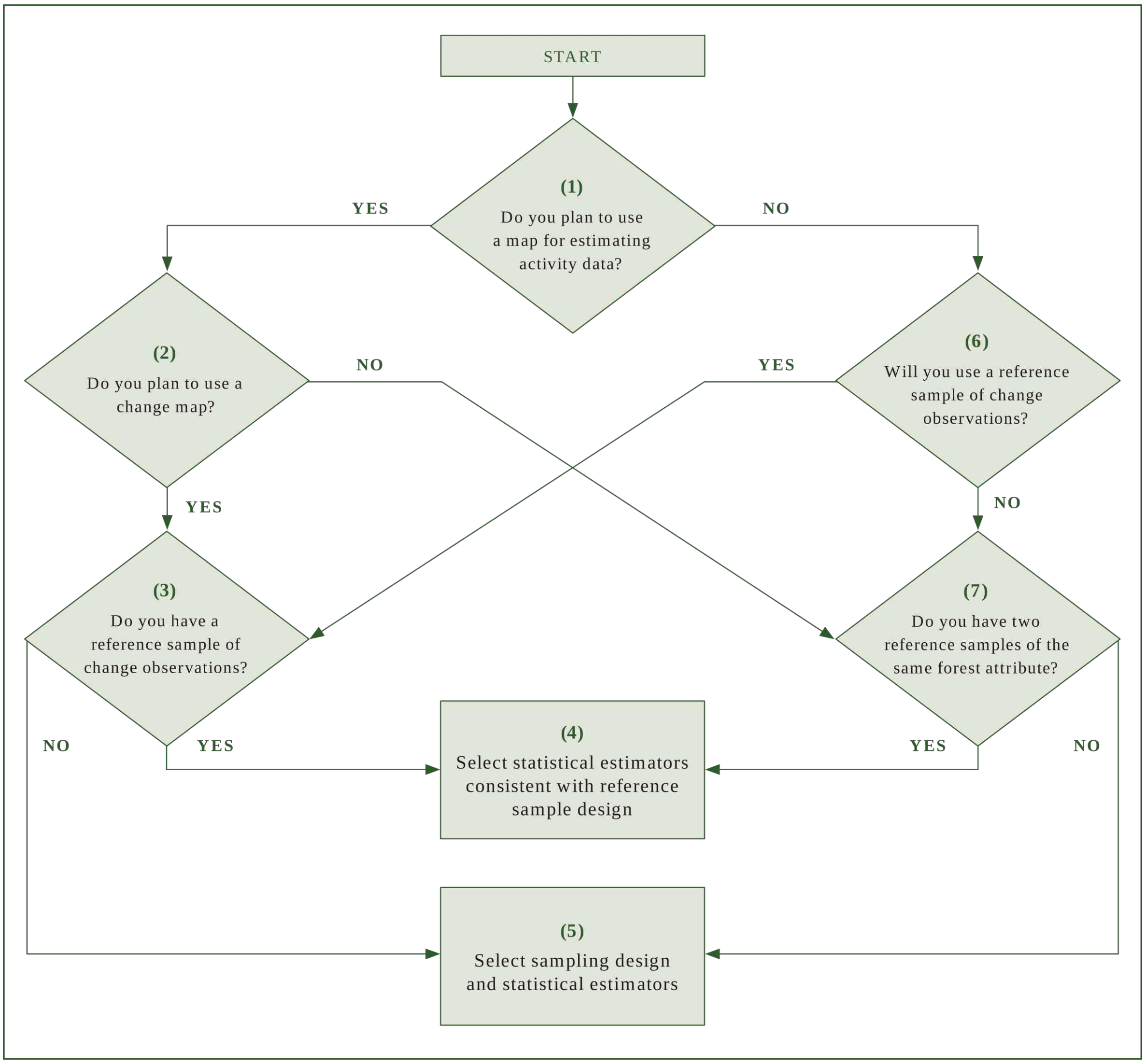
For estimation of activity data, sample locations are typically randomly or systematically selected from within strata defined by the classes of an activity or land cover map (e.g. deforestation, forest remaining forest). These sample locations are often evaluated via visual image interpretation. A key issue is that visual interpretations can neither be assumed to be without error, nor consistent among interpreters. McRoberts *et al.* (2018c) provided a brief review of the literature and concluded that *"visual interpretations of remotely sensed data, even by well-trained professional interpreters, are subject to substantial interpreter disagreement and error."* The effects of interpreter errors and inconsistencies are to introduce bias into the estimator of activity class areas and into the estimator of the corresponding uncertainty. Bias in the estimator of class areas increased as the number of interpreters decreased, as the land-cover class map and interpreter accuracy decreased, as the between-interpreter correlations increased and as the relative land cover map class sizes changed. Standard errors of class area estimates were underestimated by a factor of approximately 1.4 when the uncertainty due to interpreter error and inconsistency was ignored. Of importance, bias in the estimator of the class errors leads to non-compliance with the first IPCC good practice guideline regarding neither over- nor under estimation, and bias in the estimator of uncertainty precludes the ability to reduce uncertainties as per the second IPCC good practice guideline. Several steps can be used to mitigate these adverse effects. First, the bias of the estimator can be decreased by using more interpreters, perhaps as many as 5-7, by common training regimes, and by seeking consensus among interpreter disagreements following independent interpretations. The latter step could involve a review of reference labels with small confidence levels or conflicting labels by a team that includes interpreters and seniority. Second, a form of hybrid inference described by McRoberts *et al.* (2018c) incorporates the effects of interpreter error and inconsistency in the uncertainty estimation.

Once a sample of reference observations has been collected, the area of the activity data and the associated confidence interval are estimated using a statistical estimator corresponding to the sampling design.

Some commentary is in order regarding the recommendation in **Volume 4, Chapter 3, of the 2019 Refinement** (IPCC, 2019) that map accuracy be estimated and expressed using the indices in Congalton (1991). Although map accuracies are informative, they do not directly produce activity class area estimates or the uncertainties of the estimates. Further, any sampling for reference data should be optimised for estimation of activity data, not map accuracies. Finally, Congalton (1991) illustrates the use of the Kappa index which is elsewhere strongly discouraged because it does not serve a useful role in accuracy assessment or area estimation (Foody, 2020; Olofsson *et al.*, 2014; Pontius and Millones, 2011; Strahler *et al.*, 2006).

The decision tree in **Figure 19** and the following decision point discussion is intended to help users decide which sampling designs and estimators to use given the nature of the maps and available reference data.

Figure 19: Guidance on choosing inference framework for estimation of activity data



Considerations for 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. 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.. The primary advantages of using maps are

1. that spatially-explicit analyses are possible; and

2. 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. Furthermore, **decision 4/CP.15** requires Parties to establish an NFMS that provide estimates that are transparent, consistent, as far as possible accurate, and which reduce uncertainties, taking into account national capabilities and capacities. An underlying assumption in **Figure 19** 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. If the reference sample of change observations is already available, then the selection of a statistical estimator and inferential approach is limited by the sampling design used to acquire the change reference data. If the reference sample is yet to be acquired, then greater flexibility is possible in the choice of the combination of sampling design, estimator and inferential approach.

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 the 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 Good practice is defined by the 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 maximise precision without introducing bias, given the level of resources reasonably available for GHGI development. 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 minimise 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.*, 2016a).

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 32** and **Box 33** 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. As explained in Decision Point 5, the stratified approach illustrated in **Box 32** is particularly useful when the strata correspond to activities. The model-assisted approach in **Box 33** 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 32: A stratified approach to accuracy assessment and area estimation

The examples presented in this Box refers to decision points in **Figure 19**.

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 percent of the total area, an 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 **Table 15**), which uses the numerical data provided in the two previous paragraphs).

Table 15: Error matrix of sample counts

Strata	Deforestation	Forest gain	Stable forest	Stable non-forest	Total	$A_{m,h}$ [ha]	w_h
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

Strata	Deforestation	Forest gain	Stable forest	Stable non-forest	Total	$A_{m,h}$ [ha]	w_h
Total	69	56	175	340	640	900 000	1

Note: Table rows are Map classifications, Table columns are Reference classifications.

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_{hi} is denoted as $\hat{p}_{hi}$, where h denotes the row and i 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, the following estimator can be used:

Equation 16

$$\widehat{p}_{hi} = W_h \frac{n_{hi}}{n_h}$$

where W_h is the proportion of the total area in stratum (map class) h, (see the final column in **Table 15**) and n_h is n_{hi} summed over i. Accordingly, the error matrix may be expressed in terms of estimated area proportions,$\hat{p}_{hi}$ (see **Table 16**), rather than in terms of sample counts, n_{hi} (see **Table 15**).

Table 16: Error matrix of estimated area proportions

Strata	Deforestation	Forest gain	Stable forest	Stable non-forest	Total (w_h)	$A_{m,h}$[ha]
Deforestation	0.0176	0	0.0013	0.0011	0.02	18,000
Forest gain	0	0.011	0.0016	0.0024	0.015	13,500
Stable forest	0.0019	0	0.2967	0.0213	0.32	288,000
Stable non-forest	0.004	0.002	0.0179	0.6212	0.645	580,500
Total	0.0235	0.013	0.3175	0.646	1	900,000

Note: Table rows are Map classifications, Table columns are Reference classifications.

Once $\hat{p}_{hi}$ is estimated for each element of the error matrix; accuracies, activity areas and standard errors of estimated areas can be estimated. User's accuracy, $\hat{U}_h = \hat{p}_{hh} \div \hat{p}_{h+}$, producer's accuracy, $P_i = \hat{p}_{ii} \div \hat{p}_{+i}$, and overall accuracy, $\hat{O} = \sum h = 1^H \hat{p}_{hh}$, where H denotes the number of strata (i.e. 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 **Table 15**, because the sample is stratified.

The estimated area proportions in **Table 16** are then used to estimate the area of each reference class. The row totals of the error matrix in **Table 17** are the map class area proportions (W_h), while the column totals are the estimated reference class area proportions.

Using the notation of **Equation 30**, and adding the subscript i to indicate reference class i,

Equation 17

$$\widehat{\mu}_i = \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi}$$

but because

Equation 18

$$y_{hi} = \begin{cases} 1 & if \quad h = i \\ 0 & if \quad h \neq i \end{cases}$$

Equation 15 can be expressed as,

Equation 19

$$\widehat{\mu}_{hi} = \frac{n_{hi}}{n_h}$$

so that from **Equation 31**

Equation 20

$$\widehat{\mu}_i = \sum_{h=1}^{H} W_h \widehat{\mu}_{hi} = \sum_{h=1}^{H} W_h \frac{n_{hi}}{n_{h+}} = \sum_{h=1}^{H} \widehat{p}_{hi}$$

The area for reference class j is estimated as the product of $\hat{\mu}_i$ and the total area, A_{tot}. For example, the estimated area of deforestation the reference data is $\hat{A}_1 = \hat{p}_{+1} \times A_{tot} = 0.235 \times 900,000 = 21,158 ha$ 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 34** and again adding the subscript to denote reference class j,

Equation 21

$$\widehat{\sigma}_{hi}^2 = \frac{1}{n_{h+} - 1} \sum_{i=1}^{n_h} (y_{hi} - \widehat{\mu}_{hi})^2$$

Noting from **Equation 18** that $y_{hi} = 0$ or $y_{hi} = 1$, **Equation 21** can be expressed as,

Equation 22

$$\widehat{\sigma}_{hi}^2 = \frac{1}{n_{h+} - 1} \sum_{i=1}^{n_h} \widehat{\mu}_{hi}(1 - \widehat{\mu}_{hi})$$

so that from **Equation 32**

Equation 23

$$\widehat{V}(\widehat{\mu}_i) = \sum_{h=1}^{H} W_h^2 \frac{\widehat{\sigma}_h^2}{n_h} = \sum_{h=1}^{H} W_h^2 \frac{\widehat{\mu}_{hi}(1 - \widehat{\mu}_{hi})}{n_h - 1} = \sum_{h=1}^{H} \frac{W_h \widehat{p}_{hi} - \widehat{p}_{hi}^2}{n_h - 1}$$

and standard error,

Equation 24

$$SE(\widehat{\mu}_i) = \sqrt{\widehat{V}(\widehat{\mu}_i)}$$

From **Equation 24**, so that the standard error for the estimated area of forest loss is $\mathrm{SE}(\hat{\mathrm{A}}_1) = \mathrm{SE}(\hat{\mu}_1) \times \mathrm{A}_{\mathrm{tot}} = 0.0035 \times 900,000 = 3,142\mathrm{ha}$. A 95 percent confidence interval of the estimated area of forest loss is $+/-1.96 \times 3142 = +/-6158\mathrm{ha}$. Estimates and confidence intervals for all classes are shown in **Table 17**.

Table 17: Area estimates, standard errors and upper and lower 95% confidence interval limits

Strata (j)	$\hat{\mu}_i$ **[proportion]**	$\mathrm{SE}(\hat{\mu}_i)$ **[proportion]**	$\hat{\mu}_j$ **[ha]**	**Lower 95% confidence interval [ha]**	**Upper 95% confidence interval [ha]**
Deforestation	0.0235	0.0035	21 158	15 000	27 315
Forest gain	0.013	0.0021	11 686	7 930	15 442
Stable forest	0.3175	0.0088	285 770	270 260	301 280
Stable non-forest	0.646	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 implementation of the sampling design).

Box 33: 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 i^{th} segment consisted of the proportion of pixels, $\widehat{y}_i$, 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 i^{th} 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 generalised regression (GREG) estimator is more suitable than the stratified estimator used in Example 1.

Estimation

For each time interval, consistent with the notation used for **Equation 38** and **Equation 39** above, the map-based estimate of proportion of deforestation area was,

Equation 25

$$\widehat{\mu}_{map} = \frac{1}{N}\sum_{i=1}^{N}\widehat{y}_i$$

where $N = 25000$ 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,

Equation 26

$$\widehat{Bias}(\widehat{\mu}_{map}) = \frac{1}{n}\sum_{i=1}^{n}(\widehat{y}_i - y_i)$$

where $n = 250$ is the number of segments in the sample. The adjusted (GREG) estimate is the map estimate with the adjustment term subtracted,

Equation 27

$$\widehat{\mu}_{GREG} = \widehat{\mu}_{map} - \widehat{Bias}(\widehat{\mu}_{map}) = \frac{1}{N}\sum_{i=1}^{N}\widehat{y}_i - \sum_{i=1}^{n}(\widehat{y}_i y_i)$$

The standard error (SE) of $\hat{\mu}_{GREG}$ is,

Equation 28

$$SE(\widehat{\mu}_{GREG}) = \sqrt{\widehat{V}(\widehat{\mu}_{GREG})} = \sqrt{(\frac{1}{n(n-1)}\sum_{i=1}^{n}\varepsilon_1 - \overline{\varepsilon})^2}$$

where $\varepsilon_i = \hat{y}_i - y_i$ and $\overline{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\varepsilon_i$.

This estimator is based on an assumption of an 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 **Table 18**. In the statistical literature, these estimators are characterised 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).

Table 18: 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]**	**Lower 95% confidence interval [ha]**	**Lower 95% confidence interval [ha]**
1990-2000	0.0033	0.0012	33 000	9 480	56 520
2000-2010	0.0011	0.0012	11 000	0[a]	34 520
1990-2010	0.0044	0.0016	44 000	12 640	75 360

a. Because the lower limit was negative, it was reset to 0.

Box 34: Mitigating the impact of omission errors

The following text is based on Olofsson *et al.* (2020). Countries have reported that the presence of certain types of errors in maps gernated from remotely sensed data and used to stratify study areas have resulted in large uncertainties and large differences between mapped and estimated areas. The errors are reference observations of activities, typically deforestation or forest loss, in large strata such as stable forest. Such errors are referred to as omission errors because they represent omissions of activities of interest in the map.

The reason that omissions tend to represent a large area, even if the number of errors is small is best explained by **Equation 16**, which converts the number of sample units observed as class j in stratum h to an estimated area proportion. A typical omission error would be an observation of deforestation in the forest stratum; if the forest stratum covers 80 percent of the study area ($W_{forest} = 0.8$), and sample of 400 units were selected in the forest stratum, a single omission error would represent an estimated area of $0.8 \div 400 = 0.002$ or 0.2 percent of the study area. When applying a stratified estimator (**Equation 20**), this omitted area of deforestation would be added to the correctly mapped area, while the committed area of deforestation would be excluded. Unless the deforestation commission error is equal to, or larger than the omission, the estimated area of deforestation would be larger than the mapped area of deforestation. It is important to note in such cases that the estimated area is not wrong, even if very different from the mapped area; keep in mind that all maps have errors and that the use of an unbiased estimator accommodates the effects of map classification errors. More problematic is that impact on the width of confidence intervals for the estimates. Looking at the stratified variance estimator (**Equation 23**), we can conclude that the variance of the deforestation estimate primarily depends on the sample size in and weight of the forest stratum.

Hence, mitigating the impact of omission error can be achieved by increasing the sample size in the forest stratum and/or decreasing the weight of the forest stratum. The former approach suggests that an allocation of the sample to strata that is proportional to the size of the strata is preferable if the objective is to estimate the area of activity data. The use of non-stratified design like SRS or SYS would achieve the same. The problem of not using strata, or allocating proportionally to strata size, is that a very large sample size will be required if the areas of activity data are small. For example, if the deforestation stratum is 0.5 percent and the desired sample size in the deforestation stratum was 30, a sample size of 60 000 units would be required under SRS or STR with proportional allocation ($30/0.005 = 60000$). Such large sample sizes are often prohibitively expensive.

A more attractive solution is to try to decrease the size of the stratum in which the errors occur. Such a solution suggests that any information on where errors are likely to occur should be incorporated into the stratification. For example, if vast areas of forest were inaccessible due to terrain, legislation, etc., and forested areas in close proximity to agriculture and settlements were treated as different strata rather than just forest, it is likely that the impact of errors would be less. Following this rationale, an idea that has been explored in the literature (e.g. Arévalo *et al.*, 2020) is the use of buffer strata. A buffer stratum is typically defined as the pixels mapped as forest next to mapped activities, where omission error are hypothesised to be more likely to occur. Because the buffer stratum is considerably smaller than the rest of the forest stratum, errors in the buffer stratum would have a much smaller impact on estimates.

4.2.3.1 Estimators for use with simple random and systematic sampling designs

The simplest approach to estimating the components necessary for construction of a confidence interval is to use the familiar SRS estimators of the mean, $\hat{\mu}_{SRS}$, (also called simple expansion estimators, but referred to here as SRS estimators) and the variance of the estimate of the mean, $\hat{V}(\hat{\mu}_{SRS})$,

Equation 29

$$\widehat{\mu}_{SRS} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

and

Equation 30

$$\widehat{V}(\widehat{\mu}_{SRS}) = \frac{\sum_{i=1}^{n}(y_i - \widehat{\mu}_{SRS})^2}{n(n-1)}$$

where i indexes the n number of reference sample units and y_i is a reference sample 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.

4.2.3.2 Estimators for use with stratified sampling designs

When within strata (within map activity classes) 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 the 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. Stratified estimators for general use, not just for estimating activity data, are described in **Section 3.2.1**. STR estimators of the mean,

$\hat{\mu}_{STR}$,and the variance of the estimate of the mean, $\hat{V}(\hat{\mu}_{STR})$, are provided by Cochran (1977) as,

Equation 31

$$\widehat{\mu}_{STR} = \sum_{h=1}^{H} W_h \widehat{\mu}_h$$

and

Equation 32

$$\widehat{V}(\widehat{\mu}_{STR}) = \sum_{h=1}^{H} W_h^2 \frac{\widehat{\sigma}_h^2}{n_h}$$

where

Equation 33

$$\widehat{\mu}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi}$$

and

Equation 34

$$\widehat{\sigma}_h^2 = \frac{1}{n_h - 1} \sum_{i=1}^{n_h} (y_{hi} - \widehat{\mu}_h)^2$$

$h = 1, \ldots, H$ denotes strata; y_{hi} is the i^{th} sample observation in the h^{th} stratum; w_h is the weight for the h^{th} stratum; n_h is the number of plots assigned to the h^{th} 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 plots whose locations are based on systematic grids or tessellations and use sampling intensities that are constant over large geographical areas. This is the case in several tropical countries including Mexico and Zambia, where very large samples (n > 10 000) have been selected using an SYS design, and reference conditions at sample locations have been observed in fine resolution data and in time series of Landsat data (Oswaldo Carrillo and Abel-Mizu Siampale, personal communication). In such cases, even though stratified sampling is not possible, increased precision may still be achieved by using stratified estimation subsequent to the sampling, a technique characterised as post-sampling stratification or simply *post-stratification* (PSTR) (Cochran, 1977, p. 135). With PSTR, the same estimator, **Equation 31**, is used for the mean, but the variance estimator includes a modification (Cochran, 1977; p. 135); according to (Lohr, 2009, Eq. 4.22) if W_h is known and “n_h is reasonably large (>= 30 or so)” or “reasonably large, say >20 in every stratum” (Cochran, 1977; p. 134). The variance estimator is

Equation 35

$$\widehat{V}(\widehat{\mu}_{PSTR}) \approx \sum_{h=1}^{H} W_h \frac{s_h^2}{n}$$

For proportions (Cochran, 1977, Eq. 3.5), the variance of stratum h can be expressed as

Equation 36

$$s_h^2 = \frac{n_h}{n_h - 1} p_h (1 - p_h)$$

In a traditional error matrix, $p_h = n_{hi}/n_h$ where n_{hi} is the sample count of reference class i in stratum h. Combining Lohr's variance approximation and Cochran's expression for stratum variance gives a post-stratified variance estimator expressed using the elements of an error matrix:

Equation 37

$$\widehat{V}(\mu_{PSTR}) \approx \sum_{h=1}^{H} W_h \frac{s_h^2}{n} = \frac{1}{n} \sum_{h=1}^{H} W_h \frac{n_h p_h (1 - p_h)}{n_h - 1} = \frac{1}{n} \sum_{h=1}^{H} W_h \frac{n_{hi}(1 - \frac{n_{hi}}{n_h})}{n_h - 1}$$

4.2.3.3 Estimators for use with model-assisted designs

The essence of model-assisted estimators is that the relationship between a variable of interest, such as proportion of land use or land-use change class (Sannier *et al.*, 2014), and predictor variables, such as map classes or spectral intensities, may be used to predict the variable of interest 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 characterised as the model-assisted, generalised 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 are provided by Särndal *et al.* (1992) (see Section 6.5) as,

Equation 38

$$\widehat{\mu}_{GREG} = \frac{1}{N} \sum_{i=1}^{N} \widehat{y}_i - \frac{1}{n} \sum_{i=1}^{n} (\widehat{y}_i - y_i)$$

and,

Equation 39

$$\widehat{V}(\widehat{\mu}_{GREG}) = \frac{1}{n(n-1)} \sum_{i=1}^{n} (\varepsilon_i - \overline{\varepsilon})^2$$

where N is the number of map units, n is the reference set sample size, y_i is the observation for the i^{th} reference set sample unit, $\hat{y}_i$ is the map class, $\varepsilon_i = \hat{y}_i - y_i$, and $\overline{\varepsilon} = \frac{1}{n} \sum_{i=1}^{n} \varepsilon_i$. The first term in

Equation 38, $\frac{1}{N}\sum_{i=1}^{N}\widehat{y}_i$, is simply the mean of the map unit predictions $\hat{y}_i$, for the area of interest, and the second term, $\frac{1}{n}\sum_{i=1}^{n}\widehat{y}_i - y_i$, 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 capitalise 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.*, 2016a). Model-assisted estimators for general use, not just for estimating activity data, are described in **Section 3.2.1**.

4.3 Methods for estimating changes in carbon pools

This section discusses methods for estimating changes in carbon pools and discusses both design-based and model-based inference. In some cases, modelling is involved to establish allometrics, or more for 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 emissions 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.

4.3.1 Above- and belowground biomass

Emissions 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 **Section 2.5** require emissions/removals factors related to estimates of biomass carbon density and change in carbon density within reported forest strata. For example, **the gain-loss methods** require 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.

Where one or more rounds of National Forest Inventory exists, biomass densities (bullet point 1) may be calculated according to methods described in **Section 4.3.1.1**. Two rounds or more of NFI data are required to estimate annual rates of change in biomass density in disturbed forest (bullet point 2)(148) and

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(147) The stratification into primary forest, modified natural forest, and planted forest is consistent with the FAO Global Forest Resource Assessment. Countries may use other stratification according to national circumstances (e.g. if there is an established national stratification), or if the use of an alternative stratification will reduce the number of sub-strata required.

(148) See example of how to generate an emissions factor for managed forest in **Section 4.3**.

long-run average carbon density in planted forest (bullet point 3). In the absence of repeated measures of NFI data, National auxiliary data sets (**Section 3.2.2** and **Section 3.2.3**) combined appropriately with **Tier 3 modelling**, can improve estimations beyond what is possible with applying Tier 1 methods (IPCC, 2019).

4.3.1.1 Allometric models for biomass estimation

Aboveground volume, biomass and carbon of woody vegetation are not directly measured in the field, but are usually predicted using tree-level allometric models, with one or more easy-to-measure explanatory variables, such as species, diameter at breast height and height.

The models used to predict aboveground biomass are usually developed before or independently of the process of selecting the sample of trees to which the models are applied. Often, these models are selected from the literature, such as those documented in the **GlobAllomeTree database**. Models constructed by global or regional macro ecological zone, such as the pantropical biomass regression of Cifuentes Jara *et al.* (2015) or the Congo basin model of Fayolle *et al.* (2018) are also extensively used, at national and subnational levels. However, for the model prediction to be accurate, it is necessary that the model specifications are correct and that the sample data from which the model was developed are very similar to the population to which the model is applied. If these assumptions do not hold, the model predictions are likely to be inaccurate and the resulting errors will propagate throughout the whole estimation process. In such cases, a Tier 1 estimate based on default factors may be preferred to an estimate obtained using an inaccurate allometric model. In this regard, **Volume 4, Chapter 2, of the 2019 Refinement** states that good practice is to choose the method with the greatest accuracy and provides a generic decision tree for the selection of an appropriate allometric model to predict tree-level volume, biomass or carbon stock. **Volume 4, Chapter 4, of the 2019 Refinement** also provides updated default values of aboveground biomass stock and growth in natural forests, both primary and secondary, and forest plantations for the major global ecological zones.

Measuring belowground biomass is a more challenging and resource-consuming exercise compared with aboveground biomass. Tier 1 methods for estimating below-ground biomass growth and stocks involve the use of belowground biomass to aboveground biomass ratio. **Volume 4, Chapter 4, of the 2019 Refinement** provides updated values of ratio of belowground biomass to above-ground biomass for plantation and natural forests for the main global ecological zones. Due to limited available data on root biomass, the development of allometric models for belowground biomass has generally entailed development of generic rather than site-and species-specific relationships (Barton and Montagu, 2006; Mokany *et al.*, 2006; Ouimet *et al.*, 2008; Peichl and Arain, 2007; Xiang *et al.*, 2011; Paul *et al.*, 2013; Reich *et al.*, 2014). A first analysis of global patterns of variation in individual-tree R:S is provided by Ledo *et al.* (2018).

Non-perennial woody vegetation is likely to be the main reservoir of above and belowground carbon in land uses other than forest land. Updated default coefficients for above- and belowground biomass in agroforestry systems and perennial crop systems are provided in the **Volume 4, Chapter 5, of the 2019 Refinement**. **Volume 4, Chapter 8, of the 2019 Refinement** also provides updated default values for tree carbon accumulation and crown-cover growth rate in urban trees.

Box 35: Appropriate domain of generic allometric models

Recent studies in woodlands (Williams *et al.*, 2005), eucalypt forests (Montagu *et al.*, 2005) and mixed-species plantings (Paul *et al.*, 2013) or in multiple ecoregions in Australia (Paul *et al.*, 2016) 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, 2004 (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);Basuki *et al.*, 2009(Indonesia); Xiang *et al.*, 2011 (China); Vieilledent *et al.*, 2016 (Madagascar); Kuyah *et al.*, 2012(Kenya); Schepaschenko *et al.*, 2018(Russia); Fayolle *et al.*, 2018(Congo Basin)). Considerable caution should be applied when using generic allometric models outside their appropriate domain, and these models should be validated with local studies, either destructive (Fayolle *et al.*, 2018) or non-destructive (Momo Takoudjou *et al.*, 2018). For this reason, generalised allometrics that have entailed the use of larger pan-continental or regional data sets (Brown *et al.*, 1989; Brown, 1997; Chave *et al.*, 2005; Chave *et al.*, 2014; Zapata-Cuartas *et al.*, 2012; Fayolle *et al.*, 2018) need to be applied with caution. Verification at fine-scale of these pan-continental generalised allometrics are desirable, but should be based on large data sets (Fayolle *et al.*, 2018). In order to avoid serious error and bias, the allometric model should not be applied to trees (or other vegetation) outside the diameter range of the samples used to construct the allometric model. Recent studies have also started investigating on whether pan-tropical allometric model parameters are independent of tree size (Picard *et al.*, 2015, Peloton *et al.*, 2016), as implicitly assumed in most of the models, however more research and data seem to be needed before reaching a conclusion (Burt *et al.*, 2020).

Box 36: 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; DeWalt and Chave, 2004). In tropical forests, lianas may also constitute a non-negligible reservoir of carbon. Methods for measuring and estimating biomass of lianas are provided in Schnitzer *et al.*, 2006.

Assessing the domain of validity of tree-level allometric models

Estimating emission factors for aboveground and belowground biomass using tree-level allometric models generally involves the use of two samples:

1. the sample of trees used to construct the model, sometimes also referred to as calibration data set, such as in McRoberts *et al.* (2016a); and
2. the sample of trees to which the model is applied (sometimes also referred to as estimation data set, ibid.).

The relationship between these two samples helps to inform decisions about the appropriateness of the model. Ideally, the two samples are selected from the same population. In some cases, the calibration sample is actually a subset of the sample to which the model is applied. If so, and if an adequate sampling design is used, it can be possible to demonstrate that the model predictions are accurate. In any case, when using an allometric model with non-negligible prediction uncertainties, large area inferences must rely on model-based estimators and the validity of the inferences largely depends on the degree to which the population conforms to the assumed model. If no direct comparison is available between the biomass observations in the trees of the estimation data set and the model predictions, it is difficult to assess whether this assumption holds. The 2019 Refinement identifies a set of criteria to assess model validity (**Volume 4, Chapter 2, Figure 2.2a, in the 2019 Refinement**). This involves a thorough analysis of the metadata associated with the model, including information on the population sampled to develop the model (e.g. geographical location, ecoclimatic conditions, plant vegetation components, species functional traits) and to the sample itself (e.g. methodology for sample selection, sample size, size range of the sampled trees, etc.). It may be worthwhile to note that some of this information is quantitative, such as sample size, and trees size range, although some is not. Contrasting this information with information related to the population from which the estimation sample is selected allows an assessment as to whether a model is suitable; the more similar the two populations are, the more unbiased the inference would be.

An obvious and fundamental prerequisite to carry out this analysis is that information for the calibration data set must be provided by the model developers. However, the scope of documentation of biomass models available in the literature varies greatly. Recent studies on biomass models for the tropics have shown that documentation is deficient in almost half the published models (Birigazzi *et al.*, 2015). Models available in the literature also often do not provide essential information such as the sample size used to develop the model or the key statistics needed to estimate the model prediction uncertainty. However, methods exist to estimate the prediction uncertainty in the absence of the covariance matrix, based on the model's coefficient of determination and sample size (Magnussen and Carillo Negrete, 2015) or through simulation of pseudo-data (Wayson *et al.*, 2015). Guidelines for documenting and reporting tree allometric models are provided in Chave *et al.* (2014).

Resolving mismatches between domains of validity

If the domain of validity of the model does not match the population to which the model is to be applied, the 2019 Refinement suggests checking the possibility of acquiring new data to resolve the mismatch (**Volume 4, Chapter 2, Figure 2.2a, in the 2019 Refinement**).

This could imply carrying out a new campaign for acquiring biomass/volume measurements, thereby increasing the size of the sample used to develop the model and increasing the degree to which the model represents the population to which the model is to be applied. The **Volume 4, Chapter 2, Box 2.0c, in the 2019 Refinement9 Refinement** (IPCC, 2019) also describes evolving technologies, such as terrestrial laser scanning, providing non-destructive and highly detailed measurements independent of the size and shape of a tree that are otherwise only available from destructive methods. Data for many trees can be acquired in an efficient manner and can mostly suffice for developing new or testing the usefulness of existing allometric models for national GHG inventories.

Evaluate and compare model's accuracy

Allometric model predictions are not observations, but rather are predictions with associated uncertainty. If this uncertainty is ignored during the estimation process, the variance of the estimated population mean will necessarily be underestimated. To incorporate the allometric model prediction uncertainty in the population biomass, a form of what has come to be known as hybrid inference, as opposed to design-based inference, is used. However, recent papers on volume and biomass estimation in forests (McRoberts *et al.*, 2014, McRoberts *et al.*, 2016a; McRoberts and Westfall, 2016), have shown that the contribution of the model prediction uncertainty to the total error is negligible when three conditions are satisfied:

1. the sample used to construct the model is from the same population to which the model is applied;
2. the model construction sample has in the order of 100 observations for each species or species group; and
3. the R^2 of the model fit is on the order of 0.95.

These criteria can be used to evaluate and compare the appropriateness of tree-level allometric models to serve as a basis for inference about population parameters, in the context of large area surveys. If these criteria are not fulfilled, the contribution of model prediction uncertainty to the total error is likely to be non-negligible. These criteria are likely to be more easily fulfilled in countries that have relatively low diversity of tree species, such as in the temperate climates. In the tropics, these criteria can be met by using a combination of efficient species grouping, aimed at reducing the model R^2, and the acquisition of new biomass/volume measurements, aimed at increasing the model's sample size.

The decision tree in **Volume 4, Chapter 2, Figure 2.2a, in the 2019 Refinement** also requires the evaluation of whether the use of an allometric model provides more accurate emission estimates compared with Tier 1 methods, based on default factors. If greater quality biomass density data are available for the population to which the model has to be applied, it is possible to compare them with the biomass densities predicted using the allometric model and, on the other hand, with the default factors provided by the 2019 Refinement. If the default factors provided by the 2019 Refinement prove to be more accurate, it is recommended to discard the allometric model and use the default factors instead, or consider a different allometric model, if available.

When possible, allometric models should also be tested by comparing with direct measurements of above- and belowground 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 (Búrquez and Martínez-Yrízar, 2011), pure stands of Poplar or Norway Spruce (Pérez-Cruzado *et al.*, 2015) and mixed-species plantings across Australia (Paul *et al.*, 2013). An independent data set of non-destructive measurements of tree size obtained using terrestrial laser scanning was used in Guyana to evaluate whether and which Chave model was most suited for the national GHG inventory (Lau *et al.*, 2019).

Particular attention should be paid when using models developed after logarithmic transformations of the response and predictor variables. Log-log transformations are commonly used in developing tree-level biomass allometric models because they facilitate the estimation of the parameters by allowing the model to be expressed in linear form and removing the heteroskedasticity. However, when calculating the predictions, it is necessary to compensate for the bias that accrues when transforming back the variables to the original scale (Baskerville, 1972).

4.3.1.2 Use of biomass maps and remotely sensed data to support estimation of emissions and removals

Biomass density maps are wall-to-wall predictions of biomass for woody plants and trees. These maps typically represent aboveground biomass from which belowground biomass can also be predicted using allometric models. To date, multiple global-level biomass density maps have been published and are available (e.g. Baccini *et al.*, 2012; Saatchi *et al.*, 2011; Avitabile *et al.*, 2016). In addition, a biomass change map is now available (Santoro and Cartus, 2019), and global biomass density maps at multiple points in time using data from dedicated space-based sensors are expected (Herold *et al.*, 2019). Despite the focus on existing global biomass maps, the guidance that follows is also applicable when maps generated from remotely sensed data are locally constructed for specific applications.

The characteristics and utility of biomass maps depend on multiple factors:

- The degree to which definitions for forest and biomass used to construct a map agree with the definitions used for the national greenhouse gas inventory.
- The availability and reliability of biomass-related field data needed to construct and validate the biomass density map.
- The degree to which definitions for forest and biomass used to construct a map agree with the definitions used for the national greenhouse gas inventory.
- The availability and reliability of biomass-related field data needed to construct and validate the biomass density map.
- The availability of and access to space-based data and the attributes of those data including spatial resolution, temporal coverage and sensitivity to biomass density, particularly in large biomass areas where optical and radar sensors often saturate.
- Map construction methods, which can range from simple interpolation of field biomass estimates using spatial covariates to modelling and prediction techniques using combinations of ground and space-based data.
- The degree to which map authors provide uncertainty information or the meta-data necessary to estimate uncertainty and the manner in which uncertainty information is used to assess the bias and precision for large area biomass estimators.
- A long-term perspective that includes establishing a data protocol to assure accessible data in the future and comparability across time scales.

Estimation of emissions, removals and emissions and removals factors is based on estimation of ratios of estimates of biomass change and numbers of intervening years. Emissions and removals factors are further estimated on a per unit area basis for specific activity classes. Thus, a precursor to estimation of emissions, removals, and emissions and removals factors, regardless of how maps are used, is estimation of biomass or biomass change, which is the primary focus of this section. To this end, and with the distinction between reference and auxiliary data in mind (**Chapter 3**), biomass maps and remotely sensed data can support and facilitate estimation of biomass and biomass change in four primary ways:

1. As a source of auxiliary data for increasing the precision of estimates of emissions, removals and/or emissions and removals factors based on ground plot reference data.
2. As a source of reference data for directly estimating biomass or biomass change directly from biomass density and/or density change maps.
3. To facilitate estimation of emissions and removals factors by combining biomass density and/or density change maps with activity data.
4. To localise emissions and removals estimates by integrating biomass density and/or density change maps with other spatial data and/or Tier 3 models.

The guidance that follows, particularly for 2-4, expands and complements the principles outlined in the 2019 Refinement principles **Volume 4, Chapter 2.3.1.3, of the 2019 Refinement** (IPCC, 2019). Although country examples that illustrate operational implementation of the guidance for the four ways are few or non-existent, multiple other studies as cited below illustrate the uses.

- **Using maps as a source of auxiliary data -** Forest attribute maps, not just biomass density and density change maps, can be used as sources of auxiliary data for increasing the precision of ground plot-based estimates of both biomass and biomass change. If a probability sample is available, or a reasonable facsimile of a probability design can be constructed from disparate existing sources of ground data (**Section 4.1.1**), both the design-based post-stratified and model-assisted estimators can be used (**Section 3.2.1**). For the post-stratified approach, the map values are aggregated into a small number of contiguous classes that serve as strata. For use with the model-assisted estimator, the map values serve as predictions. (Næsset *et al.*, 2011, Næsset *et al.*, 2013; McRoberts *et al.*, 2018c; McRoberts *et al.*, 2019).

  When using maps as auxiliary data, systematic map error and uncertainty do not need to be estimated or accommodated in any way, because no bias is introduced to the estimators and the effects of uncertainty are automatically incorporated into the design-based variance estimates.

  When estimating biomass density change rather than just biomass density, applications are similar. For reference data consisting of multi-temporal observations for a probability sample of plots, a biomass density change map constructed either directly or as the difference in two biomass density maps can be used with both the post-stratified and model-assisted estimators. For reference data consisting of two sets of observations, each for a different probability sample of plots, biomass density is estimated for each time, and density change is estimated as the difference in the two biomass density estimates.

- **Using maps as a source of reference data -** In the absence of ground data, global biomass maps can be used as sources of reference data for estimating biomass. However, because the maps consist of sets of map unit predictions subject to uncertainty, compliance with the IPCC good practice guidelines requires special considerations. In particular, the map must be validated, if not in its entirety, then for a sample of its domain. Validation is in the form of a statistically rigorous test of the hypothesis of no difference between the global map-based estimate and the estimate based on the independent reference data. Four estimates are required: (1) the global map-based estimate; (2) the standard error (SE) of the global map-based estimated; (3) the reference data estimate; and (4) the SE of the reference data estimate. The global map-based estimate is simply the mean or total over all global map units in the area of interest. The corresponding SE is based on three components: (i) the covariances among the map unit values; ii) the residual differences between map unit values and reference data; and (iii) the covariances among the residual differences. Information for these components of uncertainty must be provided by the map authors, but this is seldom, if ever actually done. McRoberts *et al.* (2019) describe some approximations and bounds on the uncertainty, but the validation process would be greatly facilitated if map authors were cognisant of these requirements.

McRoberts *et al.* (2019) demonstrate three inferential approaches for obtaining the reference data estimates and their corresponding uncertainties. An underlying assumption is that the reference data estimate is of greater quality than the global map-based estimate, based on the assumed greater quality of the underlying reference data and attention to accuracy (Stehman, 2009). Two approaches use samples of local ground reference data and auxiliary data to independently predict biomass and estimate biomass. For the first approach, which requires a probability sample of local ground reference data, the design-based post-stratified or model-assisted estimators can be used to obtain the reference estimate and its SE. For the second approach, which does not require probability samples of the local ground reference data, the model-based estimators are used to obtain the reference estimate and its SE. For both approaches, the ground reference data may or may not be from a probability sample; model-based inference is used to assess uncertainty.

The third approach uses a local map of greater quality than the global biomass density map as the source of reference data. The local map is sampled to obtain reference data using any convenient sampling intensity and sampling design, although probability sampling designs greatly simplify estimation. Because the local map also consists of predictions rather than observations, the uncertainty in the local map values must be incorporated into the estimation of overall uncertainty using hybrid inference.

- **Using maps to facilitate estimation of emissions and removals factors -** For estimating emissions and removals factors, the independent local ground reference data should be acquired for activity classes determined from ground observations, harvest data, management data and similar sources. If the independent local reference data are acquired from a local map, the population of reference data represented by the map may have to be stratified by intersecting the map with an activity class map. The map-based reference data used to estimate the emissions or removals factor for a particular activity class are then drawn from the appropriate stratum.
- **Using maps to localise emissions and removals estimates -** Some countries wish to use biomass maps in conjunction with higher order Tier 3 methods that focus on national objectives, such as linking biomass and soil carbon dynamics and tracking forest land-use change over time. However, because no country examples or reports in the scientific literature of these uses are currently known, specific guidance awaits greater clarification on actual practices.

In general, the guidance is not constrained to simply biomass maps, but also to biomass change maps. In particular, when using a global biomass change map, the same approaches can be used with the provision that all the independent local reference data are also in the form of change, whether from ground sources or from a greater quality local biomass density change map.

4.3.2 Dead wood and litter pools

When land remains in a land-use category, the IPCC Tier 1 assumption is that carbon stocks in both the dead wood and litter pools do not change over time. Tier 1 default estimates of carbon stocks in dead wood and litter are available by broad forest type and climatic zone in **Volume 4, Chapter 2, Table 2.2, in the 2019 Refinement** (IPCC, 2019). Tier 2 and 3 methods to estimate carbon dynamics associated with dead wood and litter do not assume a steady state and require country-specific data. There are two methods for estimating carbon stock changes in litter and dead wood pools, the Gain-Loss Method (**Volume 4, Chapter 2, Equation 2.18, in the 2019 Refinement**) or the Stock-Difference Method (**Volume 4, Chapter 2, Equation 2.19, in the 2019 Refinement**) (see

Section 2.3.4 for a general explanation of gain-loss and stock-difference). Estimates of dead organic matter changes obtained from these higher tier methods require either detailed inventories that include repeated measurements of dead wood and litter carbon stocks, or models that simulate dead wood and litter dynamics. Countries should use higher Tier methods where dead wood and/or litter are considered **key categories** and where National data are not available, Tier 1 can be used as an interim measure until National data become available.

When forest land is converted to a new land-use category, the Tier 1 assumption is that all litter and dead wood carbon stocks are lost in the year of the land-use conversion. When non-forest land is converted to forest land, the accumulation of litter and dead wood carbon stocks starts from zero in the year of the conversion. Accumulation of litter and dead wood carbon stocks, following Tier 1 methods, are assumed to occur linearly, starting from zero. Higher Tier estimation methods may use country-specific, non-zero estimates of litter and dead wood carbon stocks in the appropriate land-use categories or subcategories. Tier 2 or 3 methods may also include dead organic matter inputs and outputs associated with the land-use change or other activities.

For the purposes of REDD+ estimation, emissions and removals associated with REDD+ activities, carbon stock changes within the litter and dead wood pools need to be obtained by sampling, ideally from the same sampling sites established for biomass estimation. If methods for estimating these pools are not already established (e.g. via an NFI), countries could apply the methods for some REDD+ activities, namely afforestation/reforestation, set out by the UNFCCC for use with afforestation and reforestation projects under the Clean Development Mechanism.(149)

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 19**). In such cases countries would have models calibrated to develop estimates for the deadwood and litter pools consistent with their identified forest strata.

4.3.3 Soil organic carbon

Although both organic and inorganic forms of carbon are found in soils, land use and management typically have a larger impact on organic carbon stocks. Consequently, the methods provided in the IPCC guidelines focus mostly on soil organic carbon in both organic and mineral soils (IPCC, 2019). Tier 1 methods for estimating CO_2 emissions and removals on organic and mineral soils are summarised below.

Stock changes in organic soils are based on emission factors that represent the annual loss of organic carbon throughout the profile due to drainage and associated management activity (e.g. fire). The Tier 1 method is presented as a series of equations in Chapters 2 and 3 of the **IPCC 2013 Wetlands Supplement** from the following management activities, so long as organic carbon remains:

- drainage and rewetting of organic soils
- fire on drained organic soils

Default emissions/removals factors for a range of climates and ecosystems associated with these management activities are also available in the **IPCC 2013 Wetlands Supplement** (listed in **Table**

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(149) See Estimation of carbon stocks and change in carbon stocks in dead wood and litter in A/R CDM project activities **EB67 report, Annex 23**.

19).

Table 19: IPCC emissions and removals factors associated with soil non-carbon dioxide emissions

Parameter	Location in 2013 Wetlands Supplement
CH_4 emissions and removals from drained and rewetted inland organic soils	**Chapter 2, Table 2.3 Chapter 2, Table 2.4 Chapter 3, Table 3.3**
N_2O emissions and removals from drained inland organic soils	**Chapter 2, Table 2.5**
CO and CH_4 emissions and removals from fires on drained inland organic soils	**Chapter 2, Table 2.6 Chapter 2, Table 2.7**
CH_4 and N_2O from mangroves	**Chapter 4, Table 4.14 Chapter 4, Table 4.15**
N_2O from aquaculture in mangroves	**Chapter 4, Table 4.15**
CH_4 from rewetted inland wetland mineral soils	**Chapter 5, Table 5.4**

For mineral soils, Tier 1 methods estimate CO_2 emissions and removals associated with the transitions from:

- forest to non-forest land uses (i.e. deforestation)
- other land uses to forest (i.e. afforestation/reforestation)

At Tier 1, the IPCC assumes that mineral soil carbon stocks do not change for land remaining in forest land use. In the context of REDD+ activities, this covers forest degradation, sustainable management of forests and conservation. The Tier 1 method is presented in Equation 2.25 in **Volume 4, Chapter 2, of the 2019 Refinement** (IPCC, 2019) results in annual change in organic carbon stocks in mineral soils. Associated emissions factors are listed in **Table 20**. The 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. 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.

Table 20: IPCC emissions and removals factors associated with soil carbon stocks

Parameter	2003 Good Practice Guidance	2006 Guidelines	2019 Refinement to the 2006 Guidelines	2013 Wetlands Supplement
Mineral Soil Organic Carbon reference carbon stocks	**Table 3.2.4 Table 3.3.3 Table 3.4.4**	**Volume 4, Table 2.3**	**Volume 4, Table 2.3 (Updated)**	**Table 5.2**
Relative carbon stock change factors	**Table 3.3.3 Table 3.4.4**	**Volume 4, Table 5.5 Volume 4, Table 5.10 Volume 4, Table 6.2**	**Volume 4, Table 5.5 (Updated) Volume 4, Table 5.5a (New) Volume 4, Table 5.5b (New) Volume 4, Table 5.5c (New) Volume 4, Table 5.10 Volume 4, Table 6.2 (Updated)**	**Table 5.3**
Drained and rewetted organic soil emission/ removal factors	**Table 3.3.5 Table 3.4.6**	**Volume 4, Table 4.6 Volume 4, Table 5.6 Volume 4, Table 6.3**	**Volume 4, Table 4.6 Volume 4, Table 5.6 Volume 4, Table 6.3**	**Table 2.1 Table 2.2[a] Table 3.1[b] Table 3.2**
Change due to fires	–	–	–	**Table 2.6 Table 2.7**

Parameter	2003 Good Practice Guidance	2006 Guidelines	2019 Refinement to the 2006 Guidelines	2013 Wetlands Supplement
Soil carbon stocks in mangroves	–	–	–	**Table 4.11**[c]

a. Emissions/removals 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 oxidised in the year of extraction.

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 carbon 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 carbon dynamics, requiring calibration and validation data.

Where soil-related emissions from either mineral or organic soils **are found to be key**, countries should aim to apply higher Tier methods.(150) Although there remains considerable disagreement about the direction and magnitude of changes in soil carbon stocks following a land use change, a literature review (Deng *et al.*, 2016) indicated that soil carbon stocks within mineral soils significantly increased after conversions from forest to grassland, but significantly declined after conversion from forest to cropland. Conversion from cropland to forest and grassland to forest, did not result in significant soil carbon stocks change. Any disturbance to organic soils is generally considered significant and will be considered key categories.

For REDD+ reporting, activity data will likely be available at either **Approach 2 or 3,** making transition matrices of changes between successive years available. While using these more detailed statistics will provide an improved estimate of annual changes in soil organic carbon stocks, care is required in dealing with the time periods over which gains or losses of soil organic carbon are computed. If Approach 2 or 3 data are used in which land-use changes are explicitly known, carbon stocks can be computed taking into account historical changes for every individual land unit. The total carbon stocks for the sum of all units is compared with the most immediate previous inventory year, rather than with the inventory of 20-years before to estimate annual changes in carbon stocks as with Approach 1 activity data. Both methods yield different estimates of carbon stocks, and use of Approach 2 or 3 data with land transition matrices would be more accurate than use of Approach 1 aggregate statistics. The effect of underlying data approaches on the estimates differs more when there are multiple changes in land-use on the same piece of land. It is noteworthy that Approach 1, 2 and 3 activity data produce the same changes in carbon stocks if the systems reach a new equilibrium, which occurs with no change in land-use and management for a 20-year time period using the Tier 1 method. Consequently, no carbon stock increases or losses are inadvertently lost when applying the methods for Approach 1, 2 or 3 activity data, but the temporal dynamics do vary somewhat. More sophisticated **integrated frameworks** can assist in overcoming some of these reporting challenges associated with soil organic carbon changes, particularly where there are multiple land-use changes

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(150) A generic decision tree for identification of the appropriate Tier to estimate changes in carbon stocks in mineral and organic soils by land-use category is presented in **Volume 4, Chapter 2, Figure 2.4 (mineral soils) and Figure 2.5 (organic soils), in the 2019 Refinement** (IPCC, 2019).

on the same piece of land.

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 of carbon emissions due to biological oxidation or fire following disturbance. Barthelmes *et al.* (2015) provide valuable advice on how existing maps combined with remotely sensed data 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.

Under some conditions, nitrous oxide (N_2O) can be released from soils. Emissions can be either direct (e.g. derived from local soil management processes) or indirect (e.g. resulting either from atmospheric deposition of nitrogen or inputs of nitrogen from leaching or run-off from elsewhere). Emissions of N_2O are increased following the addition of nitrogen fertilisers, or by any forest management practices that increase the availability of inorganic nitrogen in soils.(151) The corresponding section in the **2006GL can be found in and Volume 4, Chapter 11**. and provides guidance on how to estimate emissions of N_2O from managed soils which is cross-referenced in the guidance in the GPG2003 (see **Table 21**).

N_2O emissions would not usually represent a **key category** for forests unless lands have had heavy application of nitrogen fertiliser; 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 nitrogen fertiliser 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 21: IPCC emissions and removals factors associated with direct and indirect nitrous oxide emissions from soil

Parameter	2003 Good Practice Guidance	2006 Guidelines	2019 Refinement to the 2006 Guidelines
Emission/removal factors related to direct N2O emissions from managed soils	1.25% of applied N	**Volume 4, Chapter 11, Table 11.1**	**Volume 4, Chapter 11, Table 11.1 (Updated) Volume 4, Chapter 11, Table 11.1a (New)**
Emission/removal factors related to indirect N2O emissions from managed soils		**Volume 4, Chapter 11, Table 11.3**	**Volume 4, Chapter 11, Table 11.3 (Updated)**

4.3.4 Emissions from prescribed fires and wildfires

Biomass burning occurs in many types of land use causing emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide N_2O, for which the IPCC provides a Tier 1 methodology, as well as other gases as carbon monoxide (CO), non-methane volatile organic compounds (NMVOC)

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(151) IPCC, see **GPG2000, Chapter 4, sections 4.7 and 4.8**.

and nitrogen oxides (NO_X). In accordance with the IPCC(152) managed-land-proxy for identifying anthropogenic emissions and removals from land, when a fire occurs in a managed land, all emissions (i.e. C stock losses and non-CO_2 emissions) have to be estimated and reported in the national GHG inventory, regardless of the type of fire. Seemingly, all emissions from fires in unmanaged forests that are followed by a change in use or in the management of forest, (e.g. replaced by a forest plantation), shall be estimated and reported.

Fires in managed forest land can be subdivided into two types:

1. all fires of natural origin, as well as all those of human origin that are not directly part of activities; referred hereafter as wildfires;(153)
2. all fires that are part of activities, such as 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 do not generally imply a change in the use of land, although those may determine a change in management (e.g. from naturally regenerating forests to forest plantations). A fire that is part of any activity may instead be the precursor of a change in the use of land, as is the case when the fire is used to clear the forest land for its conversion to another use, very likely agriculture, although it may just be part of the management operations as in case of prescribed burning of forest understorey.

IPCC methodology provides different defaults for those two types as:

1. wildfires, crown fires, surface fires
2. surface fires, post logging slash burn, land clearing fire

The IPCC methodology estimates the emissions of each GHG in proportion to the amount of organic matter redoxed by the fire. It therefore requires:(154)

- the average amount of organic matter in the aboveground biomass and dead organic matter pools, and in the peat in case methods from the **2013 IPCC Wetlands Supplement,** are applied (i.e. the fuel);
- the fraction of such fuel that is actually redoxed;
- the emissions factor for each GHG, given in proportion to the redoxed organic matter. As such, on forest lands, fire is treated as a disturbance that affects not only the biomass (in particular, aboveground), but al so the dead organic matter (litter and dead wood) as the available fuel in

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(152) 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.

(153) Refer to **GPG2003 section 3.2.1.4.2** and Volume 4, **Chapter 4.2.1 and 4.2.4 of the 2006GL.**

(154) Refer to **Chapter 3, Section 3.2 of the 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.**

these debris pools is often very significant, as well as in the peat, which is particularly significant in deforested land in some regions.

Emissions of each GHG are estimated individually and then are summed to give the total GHG emissions due to the fire, as outlined in **Equation 40**.(155)

Equation 40

$$L_{fire} = A \times M_B \times C_f \times G_{ef} \times 10^{-3}$$

Where:

L_{fire} = amount of greenhouse gas emissions from fire, tonnes of each GHG (e.g. CH_4, N_2O, etc).

A = area burnt, ha

M_B = mass of fuel available for combustion, tonnes/ha. This includes above-ground biomass, litter and dead wood, and peat if methods from the IPCC Wetlands Supplement are applied (**Section 4.3.3**).

C_f = combustion factor, dimensionless

G_{ef} = emission factor, g/kg dry matter burnt

The location of relevant IPCC Tier 1 factors are summarised in **Table 22**.

Table 22: IPCC emissions factors for prescribed fires and wildfires

Parameter	2003 Good Practice Guidance	2006 Guidelines	2019 Refinement to the 2006 Guidelines
Fuel burnt (MB)	**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)		
Non-CO_2 emissions from fuel stock loss (G_{ef})	**Table 3.A.1.15**	**Volume 4, Table 2.4 Volume 4, Table 2.5**	**Volume 4, Table 2.4 (Updated) Volume 4, Table 2.5**
Combustion factor (C_f)	**Table 3A.1.12**	**Volume 4, Table 2.6**	**Volume 4, Table 2.6 (Updated)**
N/C ratio for the fuel burnt	0.01	0.01	0.01

Tiers 2 or 3 are required where burning is a **key category** of GHG emissions(156) and require a more refined application of **Equation 40**. Countries applying higher tiers are likely to have national data at a disaggregated level on the mass of fuel available according to forest types and management systems. Higher tier estimation methods may also be able to distinguish fires burning at different intensities, resulting in different amounts of fuel consumption. Fully integrated, mass-balance Tier 3 methods can 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, as well as the meteorological conditions, including the degree of aridity. These methods also estimate the subsequent recovery from

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(155) See Equation 2.27 in **Volume 4, Chapter 2, Figure 2.6, in the 2019 Refinement** (IPCC, 2019).

(156) See the Decision Tree in **Volume 4, Chapter 2, Figure 2.6, in the 2019 Refinement** (IPCC, 2019). In situations where countries determine emissions from fire are a **key category**, efforts should be made towards the collection of National specific information related to the parameters listed in **Table 22**. In the interim, Tier 1 default estimates can be used.

fire (uptake of CO_2) and lagged emissions from dead organic matter resulting from the fire occurrence.

In general, care has to be taken in estimating carbon stock losses in the biomass pool caused by fires. Indeed:

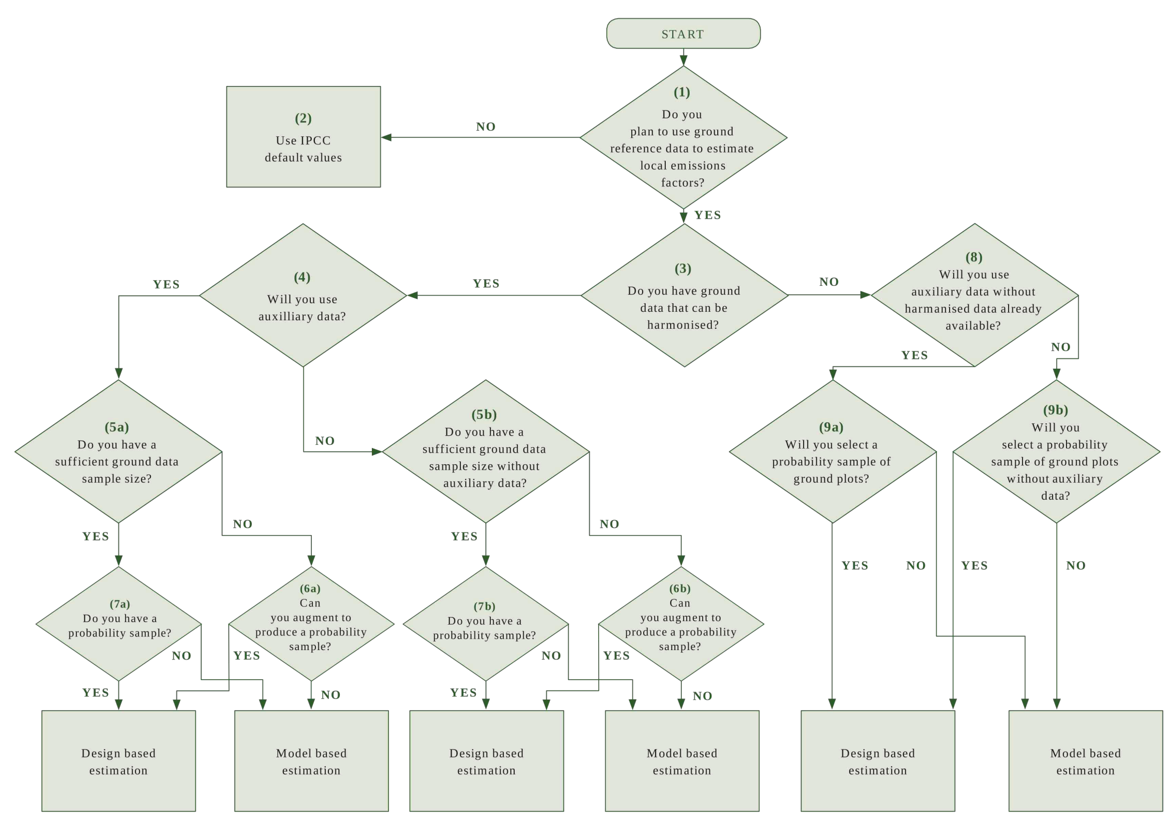
- CO_2 emissions are estimated as C stock losses, so no need to report such emissions within the burning reporting; the same applies to dead organic matter pools, although it does not apply to peat (indeed, CO_2 emissions from peat fires shall be estimated as part of the burning reporting).
- Although belowground biomass does not generate emissions during the fire event, forest fires can cause carbon stock loss where trees are killed; that below-ground biomass loss shall be reported within the carbon pool reporting of the relevant land-use category.

4.4 Inference

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 decision tree in **Figure 20** is intended to guide countries through the choices likely to arise in practice when considering the use of available data to estimate changes in carbon stocks from either design-based or model-based estimation.

Figure 20: Guidance on choosing inference framework for estimation of changes in carbon pools



Considerations for the decision points in the tree are as follows:

Decision Points 1 and 2. Use ground reference data

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 designs to estimate emission and removal 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 (i.e. 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 emissions/removals factor estimates. 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 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. If ground data are not available and exploratory analysis suggests that the categories under consideration are likely to be key, the answer at Decision Point 1 should be **Yes**, followed by **No** at Decision Point 3, in order to proceed down the right-hand side of the decision tree.

Decision Point 3. Do you have data that can be harmonised?

Harmonisation entails aligning data following a common set of criteria, 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 harmonised (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 emissions/removals 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 Decision 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 **Appendix A**. 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 Decision Point 5a, then at Decision Point 6a the sampling will need augmentation as described under supplementary sampling in **Appendix A**.

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 harmonised 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 data set 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 factor estimates within the strata are defined using auxiliary data to meet 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 A**. The individuals to be sampled will depend on the purpose of the sampling as described in **Appendix A**. 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 so that the confidence interval for model outputs of interest (e.g. carbon densities) meet 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 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?

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 appropriate model specification as the basis for valid inference and to minimise 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 models, and there may be no way to evaluate where the model results in bias estimates. 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.

4.4.1 Design based inference

4.4.1.1 Emissions and removals factors

Emissions and removals factors enable estimates of changes in carbon stocks within forest ecosystem pools (e.g. live biomass, dead wood, litter) following land disturbances (i.e. either land-use changes such as deforestation and reforestation or activities that influence stocks, but do not result in a land-use change, such as forest management activities or degradation). Countries may develop country-specific carbon stock estimates, carbon density estimates, emissions and removals factor estimates, and/or other relevant data (Tiers 2 and 3) by individual ecosystem pool and, when data and national circumstances allow, forest ecosystem condition (e.g. primary forest, secondary forest).

The **methods for estimating emissions and removal factors from each REDD+ activity** require estimates of carbon density and change in carbon density for each of the reported IPCC categories and any nationally specific sub-categories adopted (**Section 2.3.1** and **Section 2.3.3**). Ideally, the optimum conditions for generating emissions and removals factors are compiled using repeat measures from inventories with consistent field methods and known time between measurements, but often only a single known carbon stock or carbon density estimate is used and the gains and losses are modelled or estimated using auxiliary data, published estimates, or default factors.

The following information is required to generate emissions factors for a land-use change or a disturbance within forest lands:

- Biomass carbon densities in primary forest, modified natural forest, and planted forest stratified as required by forest type, and management regime or likelihood of disturbance (**Section 2.3.3**). The stratification into primary forest, modified natural forest, and planted forest is consistent with FAO's Global Forest Resource Assessment. Countries may use other stratification according to national circumstances (e.g. if there is an established national stratification or if the use of an alternative stratification will reduce the number of sub-strata required).
- Biomass carbon densities in the reported IPCC categories other than Forest, stratified as required by ecological zone, management regime and disturbance.
- 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.

Whilst Tier 1 default emissions factors are available in the IPCC Guidance and Guidelines, countries are encouraged to generate Nationally specific emissions and removals factors for **key categories (and pools).**(157) Nationally specific emissions/removals factors can be generated for two common change states as follows:

- **Emission Factor for a land-use change -** A land-use change event triggers a change in carbon between time t_1 and t_2 which results in a change in carbon density between the strata. Consider that the land-use change event is representative of deforestation, where Secondary Forest has been cleared to a cassava crop (i.e. Cropland). The above ground carbon stock at t_1 has been estimated from National Forest Inventory data and allometric models as described in **Section 4.3.1.1** and found to be 140 td.m/ha (+/- 23 td.m/ha). A study in the same ecozone as the land-use conversion estimated the aboveground biomass stock in cassava crops at t_2 to be 15 td.m/ha t (+/- 4 d.m/ha).

  The emission factor for this land-use change would be (see **Equation 41**)

  $$t_2 - t_1 = 15 - 140 = -125 d.m/ha$$

  The confidence interval associated with this emissions factor would be +/- 23.5 t d.m./ha (see worked example in **Section 4.4.1.2**).

- **Emission factor for disturbance -** A disturbance event results in a change in carbon between time t_1 and t_2 which results in a change in carbon density of the stratum forest land. This disturbance event would be representative of forest degradation where logs are removed from a Primary forest but the land use remains Forest land. The aboveground biomass of Primary forest and Secondary forest have been estimated from repeated forest inventories at the same locations as described in **Section 4.3.1.1** and found to be 380 td.m/ha (+/- 57 td.m/ha) for Primary forest

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(157) In the context of results based payments some REDD+ programs, or bilateral arrangements may require national specific emissions/removals factors.

and 140 td.m/ha (+/- 23 td.m/ha) for Secondary forest.

The emission factor for this disturbance event would be (see **Equation 41**)

$t_2 - t_1 = 140 - 380 = -240 \text{d.m/ha}$

4.4.1.2 Emissions and removals factors uncertainty

Where default values are used, uncertainties for emission and removal factors and other parameters are available from the GPG2003 (or the 2006GL and the Wetlands Supplement). For Tier 2 and 3 methods uncertainties 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.

Method 1: Estimation 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 41

$$\hat{\mu}_{EF} = \hat{\mu}_B - \hat{\mu}_A$$

where $\hat{\mu}_B$ and $\hat{\mu}_A$ 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 2** in **Section 2.5.1.2**. Because the sampling in each of the strata is independent, the uncertainty of $\hat{\mu}_{EF}$ can be calculated as

Equation 42

$$\hat{V}(\hat{\mu}_{EF}) = \hat{V}(\hat{\mu}_A) + \hat{V}(\hat{\mu}_B)$$

Where $\hat{V}(\hat{\mu}_i)$ is the variance of the estimate of the respective mean (**Section 4.2.3**). Note that $\sqrt{\hat{V}(\hat{\mu}_i)}$ 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 percent confidence interval. **Equation 42** corresponds to Rule A of **Section 6.3 of the GPG2000** Corresponding to **Volume 1, Section 3.2.3.1 of the 2006GL**, which is cross-referenced in **Section 5.2.2.1** of the GPG2003. Although Rule A is expressed in terms of 95 percent confidence intervals, rather than variance. Applying this method to the example above of estimating an emission factor for land-use change the uncertainty of the emissions factor would be:

$$\widehat{V}(\widehat{\mu}_B) = (4 \div 1.96)^2 = 4.16$$

$$\widehat{V}(\widehat{\mu}_A) = (23 \div 1.96)^2 = 137.7$$

$$\widehat{V}(\widehat{\mu}_{EF}) = 137.7 + 4.16 = 141.9$$

$$95\%\ confidence\ interval = \sqrt{141.9} \times 1.96 = 23.5td.m/ha.$$

Method 2: Estimation 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,

Equation 43

$$\hat{\mu}_{EF} = \hat{\mu}_{t_2} - \hat{\mu}_{t_1}$$

Where $\hat{\mu}_{t_1}$ $\hat{\mu}_{t_2}$ and correspond to the carbon density of the forest before and after the change, respectively. The calculation of the uncertainty of the emissions/removals factor in this case depends on the sampling design, and in particular whether on 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, the overall uncertainty can be calculated in an analogous way to **Equation 42**,

Equation 44

$$\hat{V}(\hat{\mu}_{EF}) = \hat{V}(\hat{\mu}_{t_2}) + \hat{V}(\hat{\mu}_{t_1})$$

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,

Equation 45

$$\widehat{V}(\widehat{\mu}_{EF}) = \widehat{V}(\widehat{\mu}_{t_2}) + \widehat{V}(\widehat{\mu}_{t_1}) - 2r\sqrt{\widehat{V}(\widehat{\mu}_{t_2})}\sqrt{\widehat{V}(\widehat{\mu}_{t_1})}$$

where r is the correlation in biomass density from t_1 to t_2 across the sample plots.

Applying this method to the example of estimating an emissions factor for disturbance outlined above, the uncertainty of the emissions factor would be:

$$\widehat{V}(\widehat{\mu}_{t_2}) = (23 \div 1.96)^2 = 137.7$$

$$\widehat{V}(\widehat{\mu}_{t_1}) = (57 \div 1.96)^2 = 845.7$$

$$\widehat{V}(\widehat{\mu}_{EF}) = 137.7 + 845.7 - 2 \times 0.9 \times \sqrt{137.7} \times \sqrt{845.7} = 369$$

$$95\%\ confidence\ interval = \sqrt{369} \times 1.96 = 37.7td.m/ha.$$

When biomass density is positively correlated between t_1 and t_2, the final term of **Equation 45** acts to reduce the overall variance, and thus to increase the precision. More generally, **Equation 44** and **Equation 45** 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 44 and **Equation 45** represent two extreme cases, where either all the original plots were re-surveyed (**Equation 45**), or none of the original plots was re-surveyed (**Equation 44**). The intermediate 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, for example, 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 partial replacement (Ware and Cunia, 1962; Loetsch and Haller, 1964), with calculation of $\hat{V}(\hat{\mu}_{EF})$ being more complex than either of the extreme cases. Köhl *et al.* (2015) provide a more complete description of sampling with partial replacement in the context of REDD+, and also present the calculations required to estimate $\hat{V}(\hat{\mu}_{EF})$ 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 23**. If this is considered undesirable, then an alternative estimate for under sampling with partial replacement (Päivinen and Yli-Kojola, 1989) can be used instead. The calculation is described in **Box 37**.

Uncertainties in the estimation of emissions/removals 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 $\hat{V}(\hat{\mu}_{EF})$ may need to be calculated using the estimators appropriate for a stratified sampling design, as described in **Section 4.2.3.2**. No more than 6-8 strata are generally recommended (Cochran, 1977; p134). In addition, sampling intensities within strata should be large enough to produce sample sizes of 10-20 (Cochran, 1977; Särndal *et al.*, 1992);
- 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.

The estimation of uncertainty for the emissions factor $\hat{V}(\hat{\mu}_{EF})$ given in **Equation 42** and **Equation 44** 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-to-shoot ratios for estimating belowground biomass. These additional errors can be considered independent from the sampling error, and thus the total error variance can estimated by adding them to $\hat{V}(\hat{\mu}_{EF})$. 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 to be 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, 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 be combined into a single variance term, $\hat{V}(\hat{\mu}_{\mathrm{Allom}})$, and added to $\hat{V}(\hat{\mu}_{\mathrm{EF}})$ to provide an estimate of total error.

Box 37: Estimation of the uncertainty of emissions/removals factors under sampling with partial replacement

Sampling with partial 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:

n_{12}: The number of common or permanent plots across both t_1 and t_2.

n_1: The total number of plots at t_1.

n_2: The total number of plots at t_2.

n_{1+}: The number of plots unique to t_1.

n_{+2}: The number of plots unique to t_2.

${s_{t_1}}^2$, ${s_{t_2}}^2$: The variance of the measured carbon density at times t_1 and t_2.

r: The plot-level correlation in carbon density between t_1 and t_2.

From this information two weighting parameters are calculated:

Equation 46

$$A = \frac{n_{12}(rn_{+2} + n_1)}{n_1 n_2 - n_{+2} n_{1+} r^2}$$

Equation 47

$$B = \frac{n_{12}(rn_{1+} + n_2)}{n_1 n_2 - n_{+2} n_{1+} r^2}$$

and the uncertainty of the estimate of the emissions/removals factor is given by:

Equation 48

$$\widehat{V}(\widehat{\mu}_{EF}) = \frac{A^2 s_1^2 + B^2 s_1^2 - 2ABrs_1 s_2}{n_{12}} + \frac{(1-A)^2 s_1^2}{n_{1+}} + \frac{(1-B)^2 s_2^2}{n_{+2}}$$

When all the plots measured at t_1 are also measured at t_2, then $A = B = 1$, and **Equation 48** reduces to **Equation 45**. When there are no plots in common between t_1 and t_2, then $A = B = 0$, and **Equation 48** reduces to **Equation 44**. In this latter case, $n_{12} = 0$, and the first term in **Equation 48** is undefined.

4.4.2 Model-based inference

Often, probability samples with consistent field methods and repeated and known time between measurements are not available and as such design-based inference is not possible. In such situations, countries will need to consider model-based inference (see decision tree in **Section 4.4**), as it does not require probability samples of reference data for constructing the model.

Model-based inference relies on the following underlying assumptions (McRoberts *et al.*, 2019):

- the model has been correctly specified;
- an entire distribution of possible values is assumed for each population unit (rather than just a single value); and
- randomisation is via the realised observations from the distributions characterising the population units selected for the sample.

Although probability samples may be used in model-based inference, purposive and other non-probability samples, such as those outlined in **Section 3.2.2** and **Section 3.2.3**, may also produce entirely valid model-based inferences (Särndal *et al.*, 1992,p. 534). The following steps are recommended when opting for model-based inference (IPCC, 2019):(158)

1. When selecting a model, ensure that it:
    a. adequately represents the range of land uses, ecosystems and management practices in the region or country;
    b. allows for the quantification of uncertainty;
    c. reduces uncertainty relative to other available methods (e.g. Tier 1 methods) or that estimates are improved in other ways (e.g. more complete coverage of carbon pools or lands);
    d. can be run and maintained in an operational context with available time and resources (e.g. input data are readily available, staff have sufficient experience and knowledge, suitable computing infrastructure is available);
    e. produces outputs that can be used for reporting emissions and removals by relevant land-use categories;
    f. produces time series consistent results;
    g. is compatible with other existing models used in the National Forest Monitoring System;
    h. is well documented and tested.
2. When calibrating the model:
    a. Use data that include a range of the conditions existing in the country that is representative of national circumstances.
    b. Consider model sensitivity analyses to determine the most important parameters for calibration
    c. Prepare for re-calibration of the model or modifications to the structure, if the model does not capture general trends or there are large systematic biases.

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(158) **Volume 4, Chapter 2.5, of the 2019 Refinement** (IPCC, 2019).

3. Model evaluation should:
    - a. be conducted after calibration to demonstrate that the model effectively simulates measured trends for the source category of interest;
    - b. use measurements independent of those used for model calibration when evaluating model behaviour and to confirm that the model is capable of estimating emissions and removals in the source categories of interest. In addition to evaluation with independent data, other evaluation checks may be useful, including range checks, mass balance checks, resampling methods, etc.
4. When implementing the model:
    - a. ensure sufficient computing resources and personnel time to prepare the input data, conduct the model simulations, and analyse the results.
5. Quantification of Uncertainty:
    - a. can be done using Monte Carlo analyses or be empirically based on an evaluation of model prediction error for sites with known inputs;
    - b. can be done at national scales on annual time steps for reporting but may also be estimated at finer spatial and temporal scales;
    - c. using Monte Carlo simulations may not be feasibly or sensibly applied at every spatial unit in a country or for each year. For example, in the case where only the activity data time series has been updated, but no other material changes to the inventory have been made, uncertainty estimates can be extrapolated to the additional years in the time series. A smaller test may also be run to demonstrate that there has been no material change in uncertainty.
6. Verification of estimates with independent data:
    - a. can be difficult because alternative measurements often do not exist at national scale;
    - b. may be possible at a component level. For example, model-derived estimates of timber harvest can be compared against independent data, such as timber production statistics;
    - c. can also be based on measurements from a monitoring network or from research sites that were not used to calibrate model parameters or evaluate model behaviour.
7. Reporting and documentation should be systematic and transparent and include:
    - a. a description of the model, why it was chosen and any likely consequences if the model is used outside the domain that the model is parameterised to simulate;
    - b. a description of the calibration process;
    - c. results of the analysis verifying model behaviour using independent measurements to confirm that the model is capable of estimating carbon stocks, stock changes and/or emissions and removals in the source/sink categories of interest. The sources of independent data should also be documented;
    - d. an overview of procedures that are used to apply the model;
    - e. a description of the approach taken to estimate uncertainty in the model outputs;
    - f. a summary of the verification results for the inventory;
    - g. information on the QA/QC steps.

Chapter 5 Integration and Estimation

Estimating CO_2 and non-CO_2 emissions/removals requires the integration of areas of land-use change (i.e. activity data) with data related to land management and pre- and post-disturbance carbon pools (i.e. biomass, dead organic matter (deadwood and litter) and soil carbon stock pools) (IPCC, 2019). The type of activity data available, either Approach 1, 2 or 3, has implications for subsequent use of data in estimating emissions and removals to meet defined MRV objectives.

For countries with Approach 2 data, where information on the areas of each land-use conversion is known but is not spatially-explicit, area estimates still need to be linked to appropriate initial carbon stocks, emissions factors, etc. In some cases, this may require the assignment of the land-use conversion data to climate, and/or vegetation type, soil and management strata. This can be done by some form of sampling, scaling or expert judgement (**Section 2.3.10**). Countries should document the basis for these decisions, and any methods of verification or cross-checking of estimates that have been applied.

For countries using Approach 3 data, it is possible to apportion areas of land-use conversion by spatially intersecting the data with other spatial data sets, such as those on climate, and/or vegetation type, soil and management strata. However, it is likely that inference, for example, based on survey data and expert judgement, will be needed to apportion the land-use conversion and biophysical data by management practices as data on management practices are rarely available in spatially-explicit formats (**Section 2.3.10**).

The following summarises the principles to be followed when matching activity data with carbon stock, emissions and removals factors and other relevant data:

- match national land use classifications to as many land-use categories as possible;
- when national land use classifications do not conform to the land-use categories of these guidelines, document the relationship between classification systems;
- use classifications consistently through time and, when necessary, document any modifications made to the classification system;
- document definitions of land categories, land use area estimates, and how they correspond to emissions and removals factors; and
- match each land-use category or sub-category to the most suitable carbon stock estimates, emissions and removals factors and other relevant data.

The following are the recommended steps for matching land areas with emissions and removals factors:

1. Start with the most disaggregated land use stratification, as well as the most detailed available emissions and removals factors needed to make an estimate.
2. Include only those strata applicable in your country and use this as a base stratification.
3. Match land use area estimates to the base stratification at the most disaggregated level possible. Countries may need to use expert judgment to align the best available land use area estimates with the base stratification.
4. Assign emissions and removals factors to the base stratification by matching them as closely as possible to the stratification categories.

Where national information relating to identified key carbon pools (**Section 2.3.9**) is not available to be assigned to the disaggregated base stratification, application of Tier 1 emissions/removals factors or carbon stocks is preferred over exclusion.

According to the IPCC Guidelines, inventories consistent with good practice are those which “contain neither over- nor under-estimates so far as can be judged, and in which uncertainties are reduced as far as practicable”. This means that the IPCC Guidelines are intended to provide guidance for developing inventory estimates that are accurate, but not conservative (**Box 38**). Total uncertainty(159) is a required output of the integration and should be provided as part of the estimate. The IPCC presents two approaches to estimating uncertainty:

- **Approach 1 -** Propagation of Error; and
- **Approach 2 -** Monte Carlo analysis.

Propagation of Error can be simpler to apply but requires assumptions that frequently are not entirely met, such as lack of significant correlations among the quantities used in the inventory, uncertainties that are less than +/-30 percent of the quantity value or uncertainties that are symmetrically distributed.

Monte Carlo requires more information on the probability distributions of the data involved in the calculations and as such, generally involves assumptions and more information on the underlying processes. Its application depends on the capacity to acquire this information. Monte Carlo will be particularly appropriate to use when uncertainties are large, their distribution are non-Gaussian, and algorithms are complex functions.

Monte Carlo analysis or other statistical tools can also be used to perform a sensitivity analysis to directly identify the principal factors contributing to the overall uncertainty. Thus, a Monte Carlo or similar analysis can be a valuable tool for a **key category analysis**. The method can, for example, be used to analyse more disaggregated source categories by modelling correlations and emissions/removals factors and activity data separately to identify key parameters rather than key categories.

IPCC 2019 presents a decision tree for choosing which Approach to select for estimating uncertainty (see **Volume 1, Chapter 3, Figure 3.1a**), noting that:

- hybrid approaches are possible where the propagation technique varies among categories; and
- even when requirements for application of Approach 1 are not fully present, it can still provide useful information about the uncertainty of the inventory.(160)

Box 38: The concept of conservativeness and its application

The concept of conservativeness, in the context of accounting for mitigation results, comes from the Kyoto Protocol and the development of its accounting rules and modalities.

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(159) The measure of uncertainty will be a 95 percent confidence interval around a point estimate for the value. The quantification of uncertainty is based on the input data used in the methodology equations. The overall uncertainty of the emissions/removals is dependent on the uncertainty associated with each data variable and parameter used.

(160) Because of its simplicity compared with the Monte Carlo approach, it is recommended to also apply Propagation of Error as a quality assurance / quality control (QA/QC) tool when applying Monte Carlo.

Conservativeness:

- is not to address biases in estimates used to calculate the accounted quantity;
- applies to the accounted quantity, not to the estimates used to account for the quantity; and
- is aimed at zeroing the probability that the accounted quantity is an overestimate of the true amount of emissions mitigated.

Thus, conservativeness aims at minimising the environmental integrity risk of under-estimation or in some cases (e.g. base year estimates) over-estimation for specific accounting applications. For example:

- Under the Kyoto Protocol, in the case that expert review teams cannot agree with national estimates, an adjustment procedure is applied to a Party's national GHG inventory, according to the Article 5.2, which shall result in estimates that are conservative for the Party concerned so as to ensure that anthropogenic emissions are not underestimated and anthropogenic removals by sinks and anthropogenic base year emissions are not overestimated.
- For a CDM Afforestation/Reforestation project, estimates with high uncertainty can be used in methodologies only if such estimates are conservative. **CDM AR methodologies** provide a procedure for applying discount factors in order to make the mean estimated values of parameters conservative.
- In the case of REDD+, conservativness would aim to not overestimate removals or/ and underestimate emissions in the results, and not to overestimate emissions or/and underestimate removals in the reference level.

The IPCC Guidelines do not provide methodological guidance for conservative estimates. The rules for producing these conservative estimates are sometimes derived from consideration of IPCC uncertainty ranges.

5.1 Estimating total emissions and removals and associated uncertainty

In general terms, estimates of emissions and removals are made by adding differences in estimates of carbon stock change on a per unit area basis, multiplied by the estimate of the area in which the change in carbon occurred. Change in carbon can be estimated between time 1 (t_1) and time 2 (t_2) as either:

$\Delta C_{t_{1,2}}$ = (area of a given stratum) × (change in carbon density of the stratum)

or

$\Delta C_{t_{1,2}}$ = (area transferred between two strata) × (change in carbon density between the strata)

The methods and tiers adopted along with the integration tools used to generate these estimates will influence the steps taken in the NFMS.

Both area and carbon density estimates have uncertainties which need to be combined when estimating the uncertainty of 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 non-CO_2 greenhouse gas emissions are estimated by combining component emissions/removals factors and activity data uncertainties. Estimation of the uncertainty of area and change in area is described in **Section 4.2.3** and is expressed as the variance in the estimate of the mean, denoted by $\hat{V}(\hat{\mu}_A)$. Estimation of the uncertainty in carbon density change is described in **Section 4.4.1**, and is given by $\hat{V}(\hat{\mu}_{EF})$.

Estimates of the corresponding emissions, $\hat{\mu}_E$ are calculated as the product of the area and the emissions factor estimates,

Equation 49

$$\hat{\mu}_E = \hat{\mu}_A \times \hat{\mu}_{EF}$$

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 the GPG2003 cross-references **Section 6.3 of the GPG2000**(161) which describes Rule B for combining uncertainties when quantities are multiplied together, as in **Equation 49**. Rule B states that 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. Goodman (1960) derived an exact expression for the variance as a percentage that requires no additional information to estimate, and which is given by:

Equation 50

$$\hat{V}(\hat{\mu}_E) = \hat{\mu}_{EF}{}^2 \times \hat{V}(\hat{\mu}_A) + \hat{\mu}_A{}^2 \times \hat{V}(\hat{\mu}_{EF}) + \hat{V}(\hat{\mu}_A) \times \hat{V}(\hat{\mu}_{EF})$$

Equation 50 assumes independence of the two estimates and requires estimates of the mean and the variance of the mean for area (A) and estimates of the emissions/removals factors and their variances. An example of the calculation of total emissions from activity data and emissions factors for a single stratum is given in **Box 39**. Often, the required emissions estimate is one that combines N separate

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(161) Corresponding to **Volume 1, Section 3.2.3.1 of the 2006GL**.

stratum-level estimates, to give a total estimate for all strata combined. In this case, total emissions are the sum of the total emissions for each stratum, $\sum \hat{\mu}_{E_i} \quad (i = 1 \ldots N)$ with the variance of the estimate equal to $\sum \hat{V}(\hat{\mu}_{E_i})$.

Countries may need to estimate the uncertainty associated with a difference between a reporting period emissions or removals estimate and the FREL/FRL. **Box 39** presents a typical example of how to do this for deforestation, using the methods described in this section.

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 percent; 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 from remotely sensed burn scars and have associated uncertainties, or from ground surveys. Emissions/removals factors and uncertainty ranges are provided in Table 2.5 referenced in **Volume 1, Section 2.4 of the 2006GL**.(162) The combined uncertainty associated with these emissions can be estimated using the equations for combining uncertainties given in **Equation 44** and in **Section 4.4.1.2**.

Box 39: Applying uncertainty analysis to deforestation

This example uses the results from the change in area due to deforestation calculation described in **Box 32**, and combines it with a hypothetical change in carbon density scenario.

Step 1: Change in area of deforested land - The example in **Box 32** 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:

$$\hat{\mu}_{A_i} = 21,158 \text{ ha}$$
$$\hat{V}(\hat{\mu}_A) = 3,142^2 = 9,872$$

Step 2: Calculation of EF from the change in biomass density - The carbon density of intact forest is assumed to be 250 t C/ha, with a standard error of 25 t C/ha (corresponding to an uncertainty of 10 percent). The carbon density of the post-clearing forest is assumed to be 30 t C/ha, with a standard error of 3 t C/ha (also corresponding to an uncertainty of 10 percent). The residual carbon in the post-clearing forest arises from slash residues or patches of incomplete deforestation.

Assuming that the field survey data underlying the carbon density estimates for pre- and post- deforestation involved independent sampling, then the calculation of change in biomass

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(162) The method in **Section 3.2.1.4 of the GPG2003** indexes non-CO_2 emissions from fire to emissions from CO_2 and does not provide default uncertainty ranges.

density and its uncertainty is:

$$\begin{aligned}\widehat{\mu}_{EF} &= (250-30)\times\frac{44}{12}\\ &= 807\ tCO_2/ha\\ \widehat{V}(\widehat{\mu}_{EF}) &= (25\times 44\div 22)^2+(3\times 44\div 22)^2\\ &= 8,539\end{aligned}$$

Using **Equation 42** from Emission and removal factor uncertainties. 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 49** and **Equation 50** respectively:

$$\begin{aligned}\widehat{\mu}_{E} &= 21,158\times 807\\ &= 17,083\ \text{t}\ \text{CO}_2\\ \widehat{V}(\widehat{\mu}_{E}) &= 807^2\times 9,872,164+21,158^2\times 8,539+9,872,164\times 8,539\\ &= 1.034\times 10^{13}\end{aligned}$$

For this hypothetical example deforestation led to a loss of approximately 17.1 million tonnes of CO_2, with a standard error of $\sqrt{1.034\times 10^{13}} = 3,200,000t\ CO_2$. The 95 percent 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 percent confidence interval of 10.8 to 23.4 million tonnes of CO_2.

Box 40: 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 $\hat{\mu}_{A_i} \mathrm{ha/yr}_{(j\,=\,1\ldots N)}$, and that using methods outlined in **Section 4.2.3**, the uncertainty of each determination was estimated to be $\hat{V}(\hat{\mu}_{A_i})$ corresponding to the variance of the mean deforestation rate. In this case, for the FREL the annual area deforested averaged over the N determinations is:

Equation 51

$$\hat{\mu}_A = \frac{\sum \hat{\mu}_{A_i}}{N}$$

And the successive determinations are uncorrelated, the corresponding uncertainty is:

Equation 52

$$\hat{V}(\hat{\mu}_A) = \left(\frac{\sqrt{\sum \hat{\mu}_{A_i}}}{N}\right)^2$$

Similarly, if during the assessment period, M successive determinations of the deforestation rate are made with values $\hat{\mu}_{B_j} \mathrm{ha/yr}_{(j\,=\,1\ldots M)}$, each determination having an uncertainty of $\hat{V}(\hat{\mu}_{B_j})$ again, using the methods set out in **Section 4.2.3**, the average annual deforestation rate during the assessment period is:

Equation 53

$$\hat{\mu}_B = \frac{\sum \hat{\mu}_{B_i}}{N}$$

and the corresponding uncertainty is:

Equation 54

$$\hat{V}(\hat{\mu}_B) = \left(\frac{\sqrt{\sum \hat{\mu}_{B_i}}}{N}\right)^2$$

Comparing the FREL and the assessment period, the difference in annual average deforestation rate is:

Equation 55

$$\hat{\mu}_{A\,-\,B} = \hat{\mu}_A - \hat{\mu}_B$$

and using **Equation 28** in **Box 33** the uncertainty of this difference is:

Equation 56

$$\hat{V}(\hat{\mu}_{A\,-\,B}) = \hat{V}(\hat{\mu}_A) + \hat{V}(\hat{\mu}_B)$$

Now suppose that the emissions/removals factor (the carbon density per unit area) is $\hat{\mu}_{EF} \mathrm{tCO_2/ha}$ with an uncertainty of $\hat{V}(\hat{\mu}_{EF})$. 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 57

$$\hat{\mu}_{\Delta} = \hat{\mu}_{EF} \times \hat{\mu}_{A-B}$$

with the uncertainty of $\hat{\mu}_{\Delta}$ given in **Equation 58**, consistent with **Equation 50**:

Equation 58

$$\hat{V}(\hat{\mu}_{\Delta}) = \hat{\mu}^{2}_{EF} \times \hat{V}(\hat{\mu}_{A-B}) + \hat{\mu}^{2}_{A-B} \times \hat{V}(\hat{\mu}_{EF}) + \hat{V}(\hat{\mu}_{A-B}) \times \hat{V}(\hat{\mu}_{EF})$$

The result can also be expressed in terms of a 95 percent confidence interval.

Equation 59

$$\widehat{\mu}_{\Delta} \pm t_{0.95} \times \sqrt{\widehat{V}(\widehat{\mu}_{\Delta})}$$

5.2 Propagation of error and Monte Carlo analysis

Once the uncertainties in activity data, emission factor or other parameters for a category have been determined, they may be combined to provide uncertainty estimates for the category emissions (**Section 5.1**).

They then may be combined to provide uncertainty estimates for the total national net emissions in any year and the overall inventory trend over time.

The IPCC has shown that, with the same input data, propagation of error and Monte Carlo simulation give similar results. Either Approach may be used for emission sources or sinks, subject to the assumptions and limitations of each Approach and the availability of resources.(163) In practice, however, the options are not always straightforward.

Approach 1 - Propagation of error

Approach 1 is simpler to apply but requires assumptions that frequently are not entirely met, such as lack of significant correlations among the quantities used in the inventory, uncertainties that are less than +/-30 percent of the quantity value or uncertainties that are symmetrically distributed. Approach 2 requires more information on the probability distributions of the data involved in the calculations. As such, it also involves assumptions and more information on the underlying processes and its application depends on the capacity to acquire this information. Approach 2 will be particularly appropriate to use when uncertainties are large, their distribution are non-Gaussian, and algorithms are complex functions (IPCC, 2019).

To quantify uncertainty using Approach 1, estimates of the uncertainty for each input are required, as well as the equation through which all inputs are combined to estimate an output. One propagation equation is used for addition and subtraction and another propagation equation for multiplication.(164)

Approach 2 - Monte Carlo (or similar) techniques

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 input to estimation methods. The probability distribution functions may be obtained by a variety of methods, including statistical analysis of data or expert judgement. A key consideration is to develop the distributions for the input variables to the emissions/removals calculations, so that they are based on 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 handle varying degrees of correlation (both in time and between source/sink categories). **Volume 1, Chapter 3, Section 3.2.3 of the 2006GL** provides detailed guidance on Monte Carlo methods, which are not repeated here; however, compilers are encouraged to refer to **Figures 3.6 and 3.7** which provide concise illustrations of how to apply the Monte Carlo method, in particular how uncertainties from different sources are combined to generate an overall uncertainty. If emissions and removals are estimated using a fully integrated system (**Section 2.4.2**), rather than the simple multiplication of

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(163) Figure 3.1a in **Volume 1, Chapter 3, Section 3.1.2 of the 2019 Refinement** (IPCC, 2019), which shows a basic step-by-step process for choosing an approach.

(164) see Equation 3.1 and 3.2 respectively, which have been updated in **Volume 1, Chapter 3, of the 2019 Refinement** (IPCC, 2019).

activity data and emissions/removals factors, the Monte Carlo analysis may be the only feasible approach for estimating the uncertainties. The input data are the same as for the propagation of error method, and (if data are available) the approach can also take account of auto- and cross-correlations, which cannot readily be included in the simple propagation of error method.

Chapter 6 Reporting and Verification

To achieve the objective of the UNFCCC, Parties need reliable, transparent and comprehensive information on GHG emissions. In previous chapters, guidance on how to best estimate emissions and removals was provided, but it is equally important to be able to report and verify those estimates. Thus, reporting and verification are essential for ensuring transparency, good governance, accountability and credibility of results, and for building confidence that resources are being utilised effectively. In order to ensure that the efforts to estimate emissions and removals will be recognised, the UNFCCC provided guidance on how to report them and has established processes to internationally verify the reported estimates for national GHG inventories (UNFCCC, 2014),(165) as well as for the REDD+ FRELs/FRLs and results. This chapter outlines the overall reporting and verification process under the UNFCCC relating to REDD+. General requirements relating to the GHG inventory including transparency, internal and external verification are outlined. Specific details on REDD+ related reporting and verification such as for FRELs/FRLs and technical annexes to the Biennial Update Reports, are elaborated.

6.1 Transparency and reporting

The general requirements for reporting and verification emanate from their objective to provide information to assess the level and trend of GHG across time, as well as their drivers, and of actions to address those; and build trust in the information provided by assuring its quality.

According to the reporting objectives, a transparent report that is comparable with those reported by others is required to provide for information that is across time:

- Complete, in the sense that it includes all information needed to understand across an established period and makes it possible to determine the:
    - levels and trends of all anthropogenic GHG fluxes across the country;
    - drivers of those GHG fluxes, and at what rate, and with which trend across time, each of these is occurring; and
    - actions/activities that have been implemented,(166) and/or are under planning, to reduce the GHG emissions, or to remove CO_2, and their results.
- Consistent, to enable tracking of actual progress across time;
- Accurate, to avoid any bias, and precise, to reduce uncertainty so far as practicable.

These reporting requirements, as regards the general reporting and verification of GHG emissions and removals, have been elaborated under the UNFCCC in the context of the following two processes:

1. The UNFCCC guidelines, which provide for the objective, scope and timing of the reporting;

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(165) An updated **Handbook for the Review of National Greenhouse Gas Inventories** is under preparation by the UNFCCC.

(166) Actions/activities are qualified and quantified by a number of indicators, such as: the time frame of implementation, as well as of the deviation of the GHG from the BAU; the BAU; the legal framework; the resources allocated; the GHG, land and pools impacted; the timing and system for monitoring.

2. The IPCC guidelines, which provide for the methods for making estimations and ensuring the quality of information formulated in good practice.(167)

Both processes are guided by five over-arching principles for reporting (**Section 2.3**). Such principles are the basis on which the IPCC has built its good practices for estimating emissions and removals of GHGs (i.e. methodological guidance, aimed at ensuring that each and any GHG estimate is always systematically neither over nor under the true value so far as can be judged and precise,(168) so far as practicable). Therefore, to be accepted within the reporting framework for mitigation under the UNFCCC, an estimate must be unbiased while its precision's requirement is subject to practical limits. These are limits that have not been established by default, since they are determined by the resources available, by the variability of the GHG fluxes, and by the complexity of the process from which are generated.

Accordingly, the verification process introduced below is required to assess if the information reported transparently, accurately, consistently, comparably and completely and that uncertainty has been reduced so far as practicable.(169)

6.2 Internal and external verification

Verification is defined by the IPCC as the collection of activities and procedures conducted during the planning and development, or after completion of an inventory, that can help to establish the reliability of its estimates and associated uncertainties.

Under the UNFCCC, verification is used within the:

- **National GHG Inventory guidelines -** in the context of the need to compare estimates prepared with Tier 3 methods and models (**para 41 of the annex to decision 24/CP.19**) with alternative independent estimates including using other Tiers. This process is implemented by the compilers of the report, and it is therefore an internal verification exercise.
- **MRV processes -** verification is the procedure of assessing the information submitted against TACCC reporting principles (**Section 2.3**), implemented by a subject external to the compilers of the GHG inventory.

Internal verification is aimed at providing information on the credibility/likelihood of the estimated emissions and removals. External verification aims to assess all information, including auxiliary data, inferences, uncertainty analysis, using comparable categorisations and formats, in order to evaluate the information's transparency, completeness, consistency and accuracy with the aim of ensuring that it is not biased.(170) Neither the UNFCCC nor the IPCC establishes a threshold for the precision since it depends on many circumstances. An established threshold may be too generous in some circumstances

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(167) “Good practice is a key concept for inventory compilers to follow in preparing national greenhouse gas inventories” defined as “a set of procedures intended to ensure that greenhouse gas inventories are accurate in the sense that they are systematically neither over- nor underestimates so far as can be judged, and that they are precise so far as practicable” and also “Good Practice covers choice of estimation methods appropriate to national circumstances, quality assurance and quality control at the national level, quantification of uncertainties and data archiving and reporting to promote transparency” (IPCC, 2019).

(168) Which is the inverse of uncertain.

(169) Such limits of practicability are subject to case-by-case consideration of the circumstances within which the estimate has been prepared.

(170) For an estimate of GHG emissions and/or removals, this means that while transparency is pivotal to allow a clear understanding of its quality, its completeness and consistency ensure that sources of bias have been avoided. However, other sources of bias may affect an estimate, such as the lack of representativeness of data used or an erroneous modelling of the source/sink process.

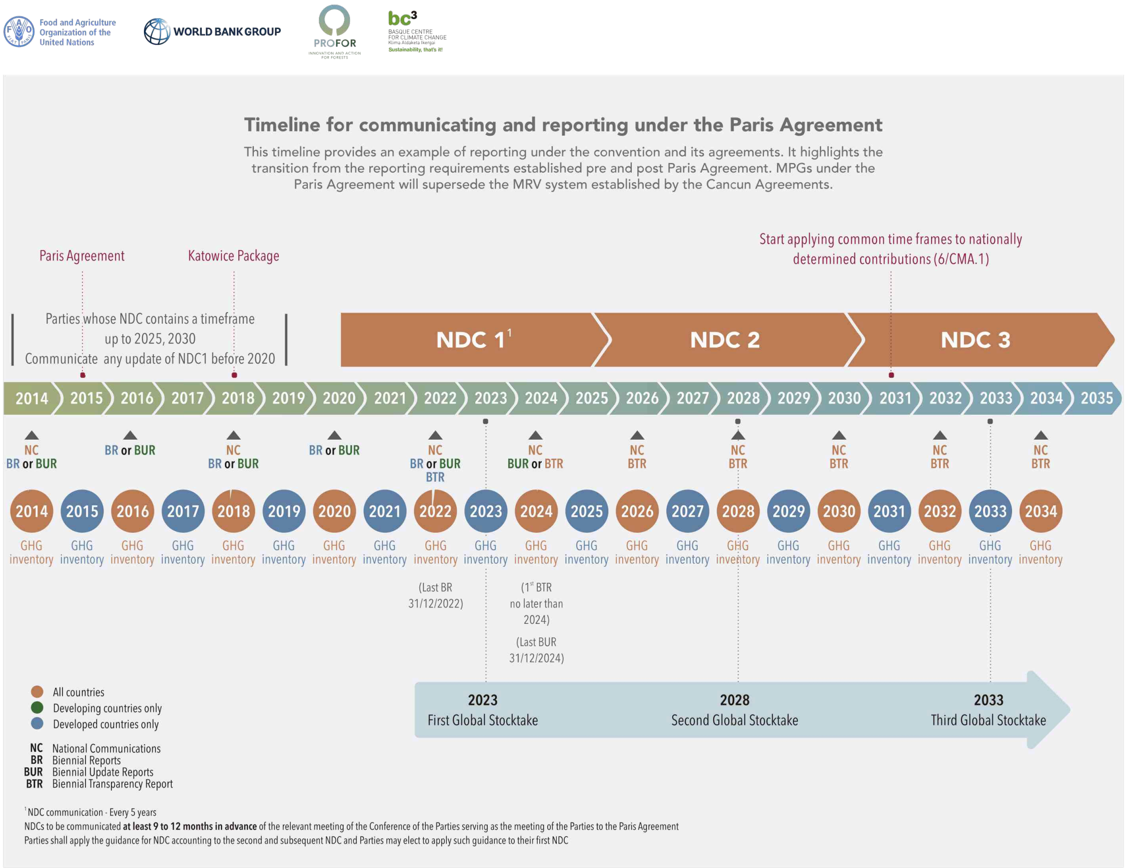
and too strict for others, depending on the context (e.g. types of forest).

Record keeping processes can assist internal and external verification processes to assess if the information is reported transparently, accurately, consistently, comparably and completely and that uncertainty has been reduced so far as practicable.

6.3 International reporting and verification processes under the UNFCCC

There are several reporting and technical assessment and review processes under the UNFCCC to which the NFMS outputs are contributing or are relevant. Reporting requirements under the UNFCCC are relatively general in nature, although have been previously different for Annex I(171) and Non Annex I countries, in terms of content and frequency. However, under the Paris Agreement, they are almost coincident, although some flexibility is recognised for developing countries, as needed. **Figure 21** shows the existing reporting requirements for developed and developing countries along an indicative timeline prior to the Paris Agreement Transparency Framework operationalisation, and after.

Figure 21: Reporting obligation and timelines for all Parties under the UNFCCC, pre and Post Paris



Source: **María José Sanz et al. (2020)**.

Since 2014, developed countries have had to submit Biennial Reports (BRs) on progress since their last NC, while developing countries submit Biennial Update Reports (BURs) to update information

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(171) As a general rule, developed countries needed to report more often and in greater detail.

in their last NC. Although both BRs and BURs should be submitted every two years (**Figure 21**),(172) developing countries have flexibility on this requirement. Before the Paris Agreement, developed countries were required to submit reports every two years and developing countries were encouraged (but not required) to do the same. Under the Paris Agreement, all countries (except LDCs and SIDS) are expected to submit reports and information every two years. LDCs and SIDS can submit reports whenever they can or want to.

6.3.1 Description of Nationally Determined Contributions

The Paris Agreement requires Parties to undertake and communicate their post-2020 climate efforts as Nationally Determined Contributions (NDCs) in order to achieve the objective of the agreement of limiting the global temperature increase to well below 2 degrees celcius while pursing efforts to limit the increase to 1.5 degrees celcius. NDCs are actions that Parties to the Paris Agreement plan to undertake to address climate change. A Party's contribution to address climate change is nationally determined according to its national circumstances and priorities. This terminology was adopted to emphasise the bottom-up (nationally determined) nature of the contributions that countries make to the global effort to address climate change, as opposed to a top-down (globally determined) approach. NDCs are recorded in a public registry maintained by the UNFCCC(173). NDCs are nationally determined and hence display a wide variety of approaches, both to format and content. This diversity is most notable in the types of target exhibited in different Parties' NDCs.

6.3.1.1 Guidance for Nationally Determined Contributions submission content and timeframes

The Paris Agreement establishes a five-year cycle for the communication of NDCs (Article 4.9). NDC submissions are due by the end of 2020, and every five years thereafter. However, since the Intended Nationally Determined Contributions (INDCs)(174) did not specify a time frame for countries, the time frame addressed in the INDCs and first NDCs varies, with the majority of countries adopting either a five-year or ten-year one. The Paris Agreement tried to accommodate both. **Paragraph 23 of decision 1/CP.21** calls on Parties with a time frame up to 2025 in their INDCs to submit a new NDC by 2020, whereas paragraph 24 calls on Parties with a time frame up to 2030 to simply update their NDC by 2020. For each five-year cycle, Parties shall submit their NDC at least 9 to 12-months in advance of the relevant session of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA). The UNFCCC Secretariat will then synthesise the NDCs in a report, which will be published before the CMA session. Beginning in 2023, a global stocktake will take place every five years to review collective progress towards achieving the objectives of the Paris Agreement. The outcomes of this stocktake are expected to inform national efforts in preparing their next NDC, for instance, the 2023 stocktake will inform the 2025 NDCs.

The Katowice Package includes guidance on what NDCs could contain and common timeframes,(175) which will guide Parties second NDCs, and any revision of their first NDC.

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(172) This timeline provides an example of reporting under the convention and its agreements by all Parties.

(173) **The interim NDC Registry**.

(174) Intended Nationally Determined Contributions were proposed ahead ahead of the Paris Agreement being finalised. As countries formally join the Paris Agreement, and look forward to implementation of these climate actions, the "intended" was dropped and an INDC converts into a Nationally Determined Contribution (NDC).

(175) **4/CMA.1** (NDC Information and Accounting), **6/CMA.1** (Common time frames for NDCs).

6.3.1.2 Nationally Determined Contributions required information

Countries are strongly encouraged to provide this information in relation to their first NDCs, submitted before the decision was taken, including when communicating or updating it by 2020. Guidance is provided for countries in communicating their second and subsequent NDC to ensure clarity, transparency and understanding of the content. This includes the following:

Reference point

- Reference year(s), base year(s), reference period(s) or other starting point(s);
- Quantifiable information on the reference indicators, their values in the reference year(s), base year(s), reference period(s) or other starting point(s), and, as applicable, in the target year;
- Other relevant information for strategies, plans and actions **Paris Agreement Article 4.6**, or polices and measures as components of NDCs;
- Target relative to the reference indicator, expressed numerically;
- Sources of data used in quantifying the reference point(s);
- Circumstances under which the Party may update the values of the reference indicators.

Time frames and/or implementation periods

- Including start and end date, consistent with any further relevant decision adopted by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA); and
- Whether it is a single-year or multi-year target, as applicable.

Scope and coverage

- General description of the target;
- Sectors, gases, categories and pools covered by the NDC, including, its consistency with IPCC guidelines;
- How the Party has taken into consideration **paragraph 31(c)[3] and (d)[4] of decision 1/CP.21**;
- Mitigation co-benefits resulting from Parties' adaptation actions and/or economic diversification plans, including description of specific projects, measures and initiatives of Parties' adaptation actions and/or economic diversification plans.

Planning processes

- Information on the planning processes that the Party undertook to prepare its NDC and, if available, on the Party's implementation plans, including, as appropriate:
    - Domestic institutional arrangements, public participation and engagement with local communities and indigenous peoples, in a gender-responsive manner;
    - Contextual matters, including, inter alia, as appropriate:
        - National circumstances, such as geography, climate, economy, sustainable development and poverty eradication;

    - Best practices and experience related to the preparation of the nationally determined contribution;
    - Other contextual aspirations and priorities acknowledged when joining the Paris Agreement;
- Specific information applicable to Parties, including regional economic integration organisations and their member States, that have reached an agreement to act jointly under **Article 4, paragraph 2, of the Paris Agreement**, including the Parties that agreed to act jointly and the terms of the agreement, in accordance with **Article 4, paragraph 16 and 18, of the Paris Agreement**;
- How the Party's preparation of its NDC has been informed by the outcomes of the global stocktake, in accordance with **Article 4, paragraph 9, of the Paris Agreement**;
- Each Party with a nationally determined contribution under **Article 4 of the Paris Agreement** that consists of adaptation action and/or economic diversification plans resulting in mitigation co-benefits consistent with **Article 4, paragraph 7, of the Paris Agreement** to submit information on:
  - How the economic and social consequences of response measures have been considered in developing the nationally determined contribution;
  - Specific projects, measures and activities to be implemented to contribute to mitigation co-benefits, including information on adaptation plans that also yield mitigation co-benefits, which may cover, but are not limited to, key sectors, such as energy, resources, water resources, coastal resources, human settlements and urban planning, agriculture and forestry; and economic diversification actions, which may cover, but are not limited to, sectors such as manufacturing and industry, energy and mining, transport and communication, construction, tourism, real estate, agriculture and fisheries.

Assumptions and methodological approaches

- Assumptions and methodological approaches used for accounting for anthropogenic greenhouse gas emissions and removals corresponding to the Party's nationally determined contribution, consistent with **decision 1/CP.21, paragraph 31**, and accounting guidance adopted by the CMA;
- Assumptions and methodological approaches used for accounting for the implementation of policies and measures or strategies in the nationally determined contribution;
- If applicable, information on how the Party will take into account existing methods and guidance under the Convention to account for anthropogenic emissions and removals, in accordance with **Article 4, paragraph 14, of the Paris Agreement**, as appropriate;
- IPCC methodologies and metrics used for estimating anthropogenic greenhouse gas emissions and removals;
- Sector-, category- or activity-specific assumptions, methodologies and approaches consistent with IPCC guidance, as appropriate, including, as applicable:
  - Approach to addressing emissions and subsequent removals from natural disturbances on managed lands;
  - Approach used to account for emissions and removals from harvested wood products;
  - Approach used to address the effects of age-class structure in forests;

- Other assumptions and methodological approaches used for understanding the nationally determined contribution and, if applicable, estimating corresponding emissions and removals, including:
  - How the reference indicators, baseline(s) and/or reference level(s), including, where applicable, sector-, category- or activity-specific reference levels, are constructed, including, for example, key parameters, assumptions, definitions, methodologies, data sources and models used;
  - For Parties with nationally determined contributions that contain non-greenhouse-gas components, information on assumptions and methodological approaches used in relation to those components, as applicable;
  - For climate forcers included in nationally determined contributions not covered by IPCC guidelines, information on how the climate forcers are estimated;
  - Further technical information, as necessary;
- The intention to use voluntary cooperation under [Article 6 of the Paris Agreement]((https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement), if applicable.

Contribution fair and ambitious, national circumstances

- How the Party considers that its nationally determined contribution is fair and ambitious in the light of its national circumstances;
- Fairness considerations, including reflecting on equity;
- How the Party has addressed **Article 4, paragraph 3, of the Paris Agreement**;
- How the Party has addressed **Article 4, paragraph 4, of the Paris Agreement**;
- How the Party has addressed **Article 4, paragraph 6, of the Paris Agreement**.

Contribution towards achieving the objective of the Convention (Article 2)

- How the nationally determined contribution contributes towards achieving the objective of the Convention as set out in its **Article 2**;
- How the nationally determined contribution contributes towards **Article 2, paragraph 1(a), and Article 4, paragraph 1, of the Paris Agreement**.

6.3.1.3 Further required accounting information

Figure 22 includes the information required to be included in the NDC in relation to further accounting needs. As indicated in the text above, Parties should strive to include all categories of anthropogenic emissions or removals in their Nationally Determined Contributions, and if any are excluded, provide an explanation. Most importantly, once a source, sink or activity is included in an NDC, it must continue to be included.

Figure 22: Elements a Party should consider when accounting for the mitigation component under the Nationally Determined Contribution

4/CMA.1 Annex II: Accounting for Parties' Nationally Determined Contributions, referred to in decision 1/CP.21, para. 31

The elements a Party should consider when accounting for the mitigation component under the NDC are established in Annex II of decision 4/CMA.1 and summarized below.

1 Accounting for anthropogenic emissions and removals in accordance with methodologies and common metrics assessed by the IPCC and in accordance with decision 18/CMA.1

- Parties whose NDC cannot be accounted for using IPCC guidelines provide information on their own methodology used (for example non quantitative policies and measures)
- If drawing on existing methods and guidance established under the Convention and its related legal instruments, provide information on how they have done so
- Provide information on methodologies used to track progress arising from the implementation of policies and measures
- If emissions and subsequent removals from natural disturbances on managed lands are addressed provide detailed information on the approach used and how it is consistent with relevant IPCC guidance
- If the effects of age-class structure in forests are addressed provide detailed information on the approach used and how it is consistent with relevant IPCC guidance
- If the harvested wood products are accounted provide information on the IPCC approach used

2 Ensuring methodological consistency, including on baselines, between the communication and implementation of NDC

- Consistency in scope and coverage, definitions, data sources, metrics, assumptions and methodological approaches
- GHG data and estimation methodologies used for accounting should be consistent with the GHG inventories
- Strive to avoid overestimating or underestimating projected emissions and removals used for accounting
- For Parties that apply technical changes to update reference points, reference levels or projections, the changes should reflect either of the following:
    i) Changes in the Party's inventory
    ii) Improvements in accuracy that maintain methodological consistency
- Parties transparently report any methodological changes and technical updates made during the implementation of their NDC

3 Striving to include all categories of anthropogenic emissions or removals in the NDC and, once a source, sink or activity is included, continuing to include it

- Account for all categories of anthropogenic emissions and removals corresponding to their NDC

4 Providing an explanation of why any categories of anthropogenic emissions or removals are excluded

Source: **María José Sanz et al. (2020)**.

There is no review process of the NDCs as such, other than the requirement to update the NDC every five years. Many Parties have formulated their NDCs as fairly high-level strategic documents, and underpinned them with more detailed action plans or roadmaps that set out how the stated objectives will be met. It is important that the NDC implementation plans and roadmaps are not stand-alone documents. If such NDC implementation plans or roadmaps do not exist, the Party may find it beneficial to develop them.

6.3.2 Reporting and reviewing of Biennial Transparency Reports

In practice, Biennial Reports require all types of information for which an NFMS is required. Hereafter, information on each Biennial Report component is provided in tables(176), with a comparison between the BURs currently submitted and the Biennial Transparency Reports that are going to be

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(176) Compilation based on BUR guidelines (**annex III of decision 2/CP.17**) and on the modalities, procedures and guidelines for the transparency framework for action and support referred to in Article 13 of the Paris Agreement (**annex to decision 1/CMA.1**).

submitted.

National Greenhouse Gas Inventory

Land use, land-use change and forestry (LULUCF) emissions and removals are reported under the UNFCCC as a sector of the GHG Inventories. Annex I Parties to the Convention submit their GHG inventories on an annual basis. **Decision 24/CP.19** provides, among others, guidance on the estimation and reporting of anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal Protocol, including from managed lands, where managed lands are those subject, or that have been subject, to human interventions and practices to perform production, ecological or social functions. Annex I Parties shall apply the **2006 IPCC Guidelines for National Greenhouse Gas Inventories** to identify sources and sinks on managed land and to report associated carbon stock changes and other emissions. The same decision encourages Annex I Parties to use the **2013 Wetland Supplement**. Further, IPCC has released the **Kyoto Protocol Supplement** and **the 2019 Refinement**. Both those additional pieces of guidance can be used by countries, subject to the justification that the selection is the most suited to the circumstances to which they are applied when compared to the guidance provided in the 2006 IPCC Guidelines.

The monitoring requirements for both BURs and BTRs include:

A. Periodic collection of information:

1. to estimate GHG emissions and removals from managed forest land across the national territory;
2. for verification of GHG estimates;
3. on the implementation of mitigation and adaptation, activities related to forest land, e.g. forest sustainable management plans, information on REDD+ safeguards.

B. Continuous collection of information on drivers of carbon stock losses, and other impacts to be mitigated, to allow measures to mitigate such losses/impacts to be taken in a timely manner.

Table 23 provides a comparison between the reporting requirements for BURs and BTRs, the later in accordance with **decision 18/ CMA.1 Annex II** in relation to the national GHGI.

Table 23: National GHGI information necessary to track mitigation progress

Elements	Biennial Update Report	Biennial Transparency Report
National Inventory Report (NIR)	Summary of National Inventory Report (NIR)	National Inventory Report, either as part of the BTR or as a stand-alone document (mandatory).
National inventory arrangements	Description of institutional arrangements	Implementation and maintenance of sustainable national inventory arrangements. Each Party shall (mandatory) report on the national focal point, the inventory preparation process, archiving of information and QA/QC and the processes for approval of the inventory.
IPCC Guidelines for the preparation of national GHG inventories	**1996GL**	**2006GL** (further encouragement to use the **2013 Wetland Supplement**). Parties shall use any subsequent version or refinement of the IPCC guidelines agreed upon by the COP / Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA).
Key category analysis	Encouraged.	Mandatory and every effort should be made to shift to higher tiers for key categories (flexibility for developing countries).

Elements	**Biennial Update Report**	**Biennial Transparency Report**
Time series	From latest year reported in the last NC submitted prior to first BUR.	Time series from 1990 (for developing countries, time series should (optional, not mandatory) go back, at least, to the base year of the NDC and should encompass all years starting from 2020).
Reporting year	The latest reporting year **shall** be no more than four years prior to the submission of the BUR (x-4)	For each Party, the latest reporting year **shall** be no more than two years prior to the submission of its national inventory report (x-2). **Flexibility** to those developing country Parties that need it to instead have their latest reporting year as three years prior to the submission of their National Inventory Report (x-3).
Uncertainty assessment and QA/QC	Encouraged.	**Mandatory**
Gases	CO_2, N_2O and CH_4 mandatory and encouragement to provide information on HFCs, PFCs and SF_6.	**Mandatory** to report on 7 gases (CO_2, N_2O, CH_4, HFCs, PFCs, SF_6 and NF_3). Developing countries can apply **flexibility** and report only on CO_2, N_2O and CH_4, but include other gases within the scope of the NDC or previously reported.
Metrics: Global Warming Potential values	IPCCs 2nd Assessment Report.	IPCCs 5th Assessment Report **(mandatory)**.

Other information necessary to track progress on mitigation in implementing and achieving its NDC

The implementation of mitigation actions requires the collection of real-time information on drivers and their occurrences (**Appendix C**), since interventions need to be taken when negative events occur (e.g. fires, illegal logging). **Table 24** provides a comparison between the reporting requirements for BURs and BTRs, the latter in accordance with Decision 18/CMA.1 Annex III, in relation to progress made in achieving mitigation goals.

Table 24: Information necessary to track progress in implementing and achieving mitigation goals

Elements	**Biennial Update Report**	**Biennial Transparency Report**
Institutional arrangements	Information on institutional arrangements and on the description of domestic MRV arrangements.	National circumstances and institutional arrangements relevant to progress made in implementing and achieving its NDC **(mandatory)**.
Description of NDC	N/A	**Mandatory:** need to include information on target and description, target year or period, reference point (base year), scope and coverage, use of cooperative approaches (market mechanisms).
Information necessary to track progress (including the use of appropriate indicators)	N/A	**Mandatory**
Mitigation policies and measures	Information in a tabular format on mitigation actions and their effects, including associated methodologies and assumptions.	Information on actions, policies and measures that support the implementation and achievement of its NDC, focusing on those that have the most significant impact on GHG emissions or removals and those impacting key categories in the national GHG inventory. This information **shall** be presented in narrative and tabular format. Each Party **should** identify policies and measures that influence GHG emissions from international transport.
Summary of GHG emissions and removals	N/A	Mandatory only if stand-alone National Inventory Report (NIR) is submitted.

Elements	Biennial Update Report	Biennial Transparency Report
Projections of GHG emissions and removals	N/A	**Mandatory** for all Parties, but encouraged for developing countries that need flexibility.

Indeed, **decision 15/CP.19** recognises the importance of addressing drivers of deforestation and forest degradation. Quantification of the effect of drivers on emissions and removals requires gathering evidence on the effect of direct causes and their occurrences, such as land clearing associated with commercial or subsistence agriculture, commercial timber extraction, fuel-wood collection and charcoal production. Taking drivers into account can be useful in stratification of lands, in ensuring consistency between historical data and reference levels and, in the case of subnational FRELs/FRLs, in monitoring displacement of emissions.

Information necessary to track climate change impacts and adaptation

The NFMS can also be used to monitor the implementation of adaptation actions (**Table 25**), including monitoring the occurrence and magnitude of non-GHG impacts and potentially to provide early warning indicators (**Appendix C**) to trigger timely implementation of appropriate mitigation measures.

Table 25 provides a comparison between the reporting requirements for BTRs in accordance with **decision 18/CMA.1 Annex IV**, in relation to the climate change impacts and adaptation activities.

Table 25: Information necessary to track progress on climate change impacts and adaptation actions

Elements	Biennial Transparency Report
National circumstances, institutional arrangements and legal frameworks relevant to adaptation actions	Parties **should** provide such information.
Information on impacts, risks and vulnerabilities	Parties **should** provide such information.
Information on adaptation priorities and barriers	Parties **should** provide such information.
Information on adaptation strategies, policies, plans, goals and actions to integrate adaptation into national policies and strategies	Parties **should** provide such information.
Information on progress on implementation of adaptation	Parties **should** provide such information.
Information on monitoring and evaluation of adaptation actions and processes	Parties **should** provide such information
Information related to averting, minimising and addressing loss and damage associated with climate change impacts	Parties **should** provide such information.
Information on cooperation, good practices, experience and lessons learned	Parties **should** provide such information.

If the NFMS is designed to to collect information on adaptation, then requirements are to:

A. Periodically collect information on the implementation of adaptation, activities related to forest land, e.g. forest sustainable management plans, information on REDD+ safeguards.

B. Continuously collect information on drivers of changes and impacts to be mitigated, to allow measures to mitigate such losses/impacts taken in a timely manner.

Information necessary to track support

Decisions 9/CP.19 and **10/CP.19** indicated the need for adequate and predictable support for the implementation of REDD+ activities, establishment of a process for coordination of support, linking 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 use of this guidance by the **GCF** when providing results-based finance. COP24 indicates the reporting requirements for BTRs (**decision 18/CMA.1 Annex V and VI**), in relation to the support provided, mobilised, needed and received.

Biennial Transparency Reports Technical Review

In addition, a review of the information reported in the Biennial Reports will be enhanced under the Paris Agreement enhanced Transparency Framework. **Table 26** and **Table 27** shows the main differences between the International Consultation Analysis (ICA) process for BURs and the Technical Review Process (TR) for BTRs. **Table 26** shows the main differences between the Technical Review Process (TR) for BTRs and the International Consultation Analysis (ICA) process for BURs.

Table 26: Comparison between requirements of Technical Analysis and Technical Expert Review

International Consultation and Analysis (ICA) of BURs	Technical Review of BTRs
Scope: Analysis of the completeness and transparency (clarity) of the information submitted.	**Scope:** Review of the consistency of information submitted. Consideration of the Party's implementation and achievement of its NDC. Consideration of the Party's support provided, if applicable. Identification of areas for improvement. Assistance in identifying capacity building needs (for developing countries).
The process shall not: review appropriateness of a Party's domestic mitigation policies and measures.	**The process shall not:** Make a political judgement; Review appropriateness of a Party's NDC or support provided; Review the Party's self-determined flexibility.
Information to be considered: National GHG inventory information on mitigation actions. Information on domestic MRV. Information on support received.	**Information to be reviewed:** Information on support received. Information necessary to track progress made in implementing and achieving its NDC. Information on financial, technology development and transfer and capacity building support provided to developing country Parties.
Format: Centralised review	**Format:** Centralised review, in-country review, desk review or simplified review.
Composition of Technical Team of Experts (TTE) Collective expertise should cover all areas of information contained in the BUR. A TTE shall include at least one Consultative Group of Experts member. The majority of experts come from Non-Annex I Parties. Geographical balance among the experts selected from Non-Annex I Parties and Annex I Parties. Each TTE shall be co-led by two experts: one from an Annex I Party and another from a Non-Annex I Party.	**Composition of Technical Expert Review Team (TERT)** Collective skills and competencies of the TERT correspond to the information to be reviewed. Balance between experts from developed and developing country Parties. Geographical and gender balance. Two lead reviewers, one from a developed country Party and another from a developing country Party. Reviews of BTRs from LDCs and SIDS will preferably be performed by technical experts from LDCs and SIDS.
Outcome: Technical Analysis Report with identification of capacity building needs.	**Outcome:** Technical Expert Review Report with: recommendations for improvement; and an analysis of capacity building needs (for developing countries).

Table 27: Comparison between requirements of facilitative, multilateral consideration of progress and Facilitative Sharing of Views

International Consultation and Analysis (ICA) of BURs	Technical Review of BTRs
Scope: Information reported by a Party.	**Scope:** Party's efforts under Article 9 of the Paris Agreement, and the Party's respective implementation and achievement of its NDC.
Information to be considered: BUR Technical Analysis Report	**Information to be considered:** BTR Technical Expert Review Report Any additional information
Format and steps: A written question and answer phase, where questions may be submitted in written form by any Party to the Party concerned. A working group session phase to take place during Subsidiary Body for Implementation sessions, open to Parties and Observers where only Parties may ask questions.	**Format and steps:** A written question and answer phase, where questions may be submitted in written form by any Party to the Party concerned. A working group session phase to take place during Subsidiary Body for Implementation sessions, open to Parties and Observers, where only Parties may ask questions.

6.4 REDD+

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 (**Section 1.3.5**) 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 28**, for:

- the periods up to 2020 linked to the International Consultation Analysis (ICA) process of the Biennial Update Reports (BURs); and
- beyond 2020 under the Technical Expert Review (TER) of the Biennial Transparency Reports. Although the transition between the two reports could be delayed up to the year 2024.

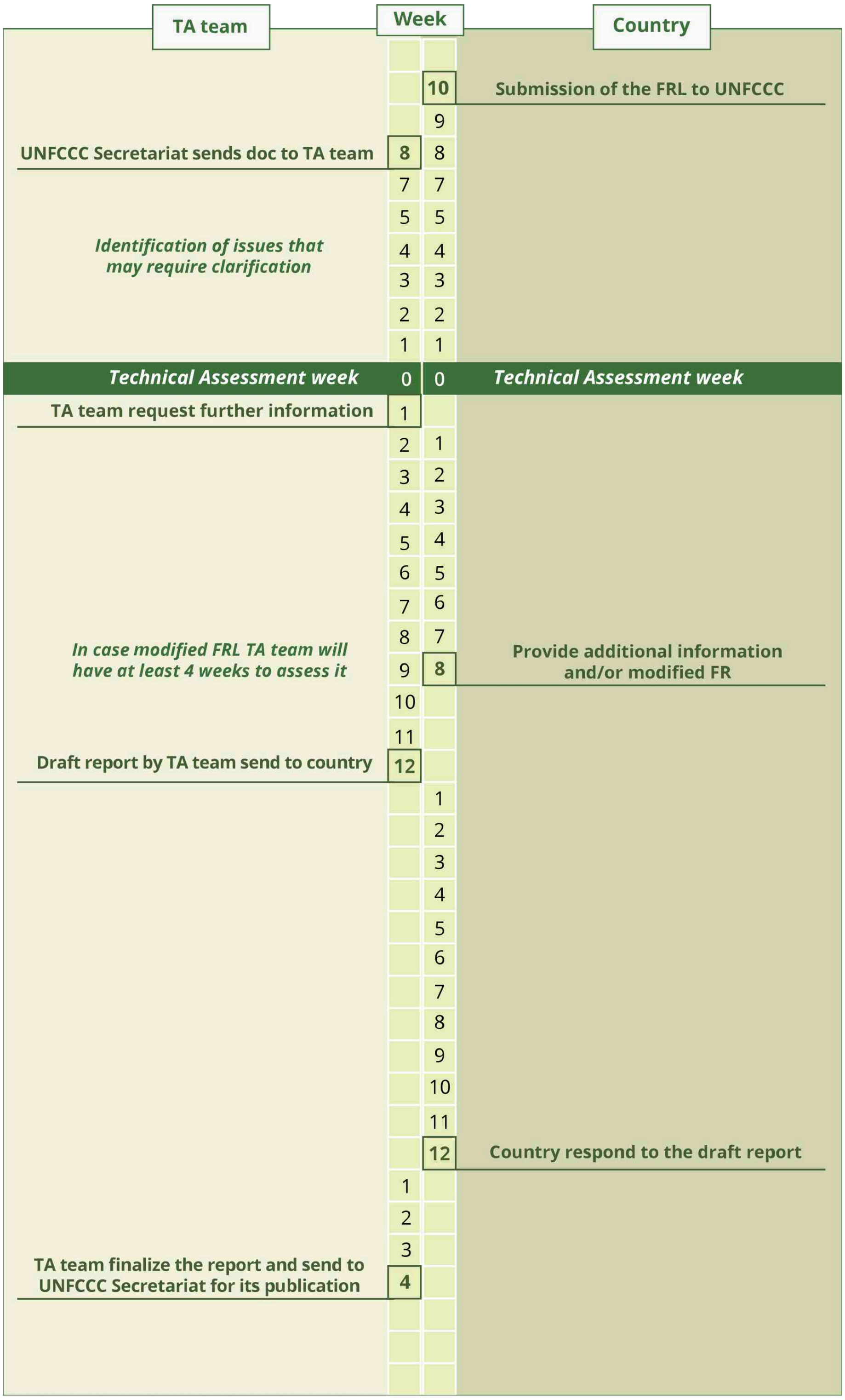
Table 28: Requirements under the UNFCCC REDD+ to access results-based payments

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	Make it publicly, including to the UNFCCC REDD+ Platform	None	In place when seeking results-based payments.	As appropriate, link to the documents.	**1/CP.16, paragraph (71a) 9/CP.19, paragraph 3&11**
National Forest Monitoring System	Make it publicly, including to the UNFCCC REDD+ Platform	None	In place when seeking results-based payments.	As appropriate, link to the documents.	**1/CP.16, paragraph (71c) 11/CP.19, & Annex 14/CP.19**
National FREL/FRL	FREL/FRL submission	Technical Assessment in the context of results-based payments	When ready (especially when seeking results-based payments)	FREL/FRL submission and Technical Assessment Report	**1/CP.16, paragraph (71b) 12/CP.17(II) Annex 13/CP.19**

Reporting and verification comprise a sequential process with initial submission and technical assessment of the FREL/FRL (**Section 6.4.2**), followed by reporting and analysis of emissions and removals associated with REDD+ activities consistent with the FREL/FRL (**Section 6.4.4**). **Figure**

23 shows the Technical Assessment process for the FRLs/FRELs in more detail.

Figure 23: FREL/FRL technical assessment process



Note: Time lines can be shortened after the review week by the Party or the TA voluntarily.

6.4.1 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.(177) An **annex to decision 12/CP.17** specifies information to be submitted on the development of FREL/FRLs, including details of national circumstances (**Section 2.5.2** discusses the interpretation of technical terms associated with FREL/FRLs). The **annex to decision 12/CP.17** stipulate that information, among 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; and
- 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 organisations, an explanation as to 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.(178)

6.4.2 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:

1. 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
2. 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

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(177) Maintaining consistency with National Greenhouse Gas Inventory approaches for AFOLU reporting is crucial to meeting the **IPCC good practice principles**. Effective **institutional arrangements** that foster close coordination between agencies involved in REDD+ and National Greenhouse Gas Inventory reporting, where they are not the same agencies, will ensure effective use of resources and improve consistency in reporting.

(178) **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."

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**. Parties are invited to submit transparent, complete,(179) 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;(180)
- 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 information reported to other international organisations, 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 construction of the FREL/FRL.

The results of the technical assessment are published on the UNFCCC web-site,(181) together with the FREL/FRL submissions and any revised submissions resulting from the technical assessment.

6.4.3 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 on a voluntary basis in the context of accessing results based payments. Beyond 2020, according to **decision 18/CMP.1, paragraph 14**, the technical analysis of the results shall be carried out concurrently with the TER under Article 13 of the Paris Agreement. Parties seeking results-based payments, which 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 the **annex to decision 14/CP.19**, data and information provided

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(179) Complete means the provision of information that allows for the reconstruction of the Forest Reference Emission levels and/or Forest Reference Levels.

(180) **Paragraph 10 of decision 12/CP.17** agreed that a step-wise approach to national FREL/FRL development may be useful, enabling Parties to improve the FREL/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**.

(181) See **the UNFCCC REDD+ Web platform**.

in the REDD+ technical annex to the BUR up to 2020 and the BTR beyond 2020 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;
   b. REDD+ activity or activities included in the FREL/FRL;
   c. territorial forest area covered;
   d. date of the FREL/FRL submission and date of the final technical assessment report;
   e. period (in years) of the assessed FREL/FRL.
2. Results in tCO_2-eq 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 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)**(182) and (d)(183) 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 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 **Section 2.3**, 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 **Section 2.5.2**.

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(182) To use the most recent IPCC Guidance and Guidelines, as adopted or encouraged by the COP, 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.

(183) 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: (1) Use a combination of remotely sensed 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; (2) Provide estimates that are transparent, consistent, as far as possible accurate, and that reduce uncertainties, taking into account national capabilities and capacities; and (3) Are transparent and their results are available and suitable for review, as agreed by the COP.

6.4.4 Technical analysis of the REDD+ annex to the BUR

Up to 2020, the technical analysis of the REDD+ technical annex to the BUR is conducted as part of the UNFCCC ICA process(184)(**Box 41**). Beyond 2020, and in accordance with **decision 18/CMP.1 paragraph 14**, the REDD+ technical annex shall be submitted as an annex to the BTR to be submitted by Parties under **Article 13 of the Paris Agreement**, and that the TA referred to in decision **14/CP.19, paragraph 11**, shall be carried out concurrently with the TER under **Article 13 of the Paris Agreement**. However, the transition between the two reports could be delayed up to the year 2024.

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 LULUCF from the UNFCCC roster of experts are to be included among the members selected for the Team of Technical Experts or the Technical Expert Review Team, which conducts a technical analysis of the BUR or the BTR, for the technical REDD+ annex.

The material submitted in the REDD+ technical annex to the BUR or BTR 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 implementation of REDD+ activities;(185)
- 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 are consistent with the guidelines for preparing the technical annex contained in the annex to **decision 14/CP.19;** and
- 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. 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; and

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(184) The COP, by **decision 1/CP.16**, decided that developing countries would submit BURs (paragraph 60) and conduct ICA of the BURs (paragraph 63), through technical analysis by a team of technical experts 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.

(185) Applied methods and approaches need to be methodologically sound and follow scientific principles.

- 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. While the scope of the technical analysis does not include the Party's national REDD+ strategy and action plan,(186) or the safeguards summary, these elements need to be provided in order to access results-based payments.(187)

Box 41: UNFCCC international consultation and analysis process and the Technical Expert Review

The modalities and guidelines for conducting International Consultation and Analysis (ICA) were adopted in Durban (**decision 2/CP.17, Annex IV**) 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(188) 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; and
- will result in a summary report.

The modalities, procedures and guidelines for conducting the Technical Expert Review were adopted in Katowice (**Annex to decision 18/CMP.1, section VII**). These modalities state that

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(186) 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.

(187) 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**.

(188) The purpose of transparency of action is to provide the UNFCCC with a 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**.

the TER process:

- Consists of:
  - A review of the consistency of the information submitted by the Party;
  - Consideration of the Party's implementation and achievement of its NDC;
  - Consideration of the Party's support provided, as relevant;
  - Identification of areas of improvement for the Party related to implementation; and
  - For those developing country Parties that need it in the light of their capacities, assistance in identifying capacity-building needs.
- shall pay particular attention to the respective national capabilities and circumstances of developing country Parties; and
- will be implemented in a facilitative, non-intrusive, non-punitive manner, respectful of national sovereignty, and will avoid placing undue burden on Parties.

Technical expert review teams shall not:

- make political judgments;
- review the adequacy or appropriateness of a Party's Nationally Determined Contribution;
- review the adequacy of a Party's domestic actions;
- review the adequacy of a Party's support provided; and
- for those developing country Parties that need flexibility in the light of their capacities, review the Party's determination to apply flexibility that has been provided for in the modalities, procedures and guidelines.

6.4.5 Additional advice on REDD+ reporting and verification

Although not set out in COP decisions the following should be included in the reports subject to technical analysis:

1. Information on methodologies is consistent between the most recent FREL/FRL submission and the REDD+ technical annex to the BUR or BTR where the results are submitted, and if any differences are observed, provide an explanation or justification.
2. The scope of the FREL/FRL and the estimates on results presented in the REDD+ technical annex are consistent with regard to the forest and other land use definitions, stratification, reported REDD+ activities and carbon pools elsewhere.(189)
3. Estimations and data sources used in the generation of estimates for both the FREL/FRL and the REDD+ annex to the BUR or the BTR (i.e. sources of ground observations and remotely sensed data) fulfil the principles of transparency, consistency, completeness and accuracy.(190) Consistency between FREL/FRLs and GHGIs is covered in more detail in **Section 2.5.2.1**.
4. Assumptions are transparently, consistently, completely and accurately reported for both the FREL/FRL report and the REDD+ annex submitted.
5. The following information on the FREL/FRL, in accordance with the technically assessed FREL/FRL, is provided within the technical annex:
    a. a summary of the data values;
    b. methodologies applied;
    c. start and end date of the historical period; and
    d. date of the FREL/FRL submission and of its final technical assessment report.
6. Estimates provided in the REDD+ technical annex are expressed in tonnes of CO_2 equivalent per year, and not in other units.
7. A description of the NFMS including institutional roles and responsibilities for measuring, reporting and verifying the results, data collection processes and how the NFMS enables the assessment of different types of forest in the country, including natural forest as defined by the

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(189) This consistency will enable a robust and complete comparison between the FREL/FRL and reported emission reductions.

(190) 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 that 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.

Party, is provided or accessible.(191)(192)(193)

8. In the case that the FREL/FRL and results are estimated at subnational level, an explanation is provided of how displacement of emissions and integration of sub national monitoring systems into national monitoring is being addressed.
9. 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. Advice on the relationship between IPCC guidance and guidelines and estimation of REDD+ activities is presented in **Section 2.5**.
10. Estimates include associated uncertainties, as these have been reduced to the extent practicable, taking into account national capabilities and capacities.
11. The results are available, suitable and presented completely to allow their reconstruction.(194)

To assess if the requirements of REDD+ technical analysis have been addressed, a country may wish to conduct an internal verification process (**Section 1.3.5**).

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(191) By referencing **decision 4/CP.15**, **decision 14/CP.19, paragraphs 9 and 11c** require Parties to use a combination of remotely sensed 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.

(192) 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 Nationally Appropriate Mitigation Actions or National Determined Contributions (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 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 implementation of the reported REDD+ activities.

(193) 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.

(194) 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.

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Appendix A Sampling

Robust and reliable estimation of carbon in forest systems based on sampling must consider the following principles:

Identifying the population

The population is the total number of items or units under consideration. Population units can range from plots to trees to points. Whichever type is chosen, the population units must be clearly identifiable, and any exclusions and their treatment noted. When sampling to construct 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 observing and measuring forest stand characteristics can vary in size, ranging from 0.01 ha to more than 1 ha, and can also include clusters of subplots (related to each other through their spatial placements) or parts of plots where only size-based subpopulations are measured. Plot shape can be related to remotely sensed data attributes (e.g. pixel size for optical sensors) and are usually rectangular, square or circular. Optimal plot size and shape will vary with forest conditions, with small area plots more typical in relatively homogeneous populations, while larger plots are more efficient for tropical forests where large trees result in large spatial variation in biomass. The combination of field and remotely sensed data may require larger plots to achieve correspondence between ground plot size and image resolution.

Selecting population units for samples

Population units are selected for samples using approaches characterised as probability-based, model-based, or purposive.

Probability-based approaches rely on assignment of a positive, known probability of selection to each population unit. Estimates of parameters such as the mean or total obtained from probability samples can readily 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 population unit. 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 homogeneous subpopulations to improve the efficiency of a given sampling effort. Design-based (or probability-based) inference requires probability samples.

Model-based sampling can be used to select individuals to optimise a feature of the model, such as the precision of the parameter estimates, coverage of the range over which the model will be applied, extremes, inflection points, or where straight line relationships are anticipated. The way the population units were selected for the sample should be transparent. Once the model has been constructed, it can be used with model-based inference to infer estimates of population parameters. Model-based inference can use, but does not require, probability samples. For example, model-based inference has been used with probability-based samples acquired using designs such as stratified random sampling (Schreuder and Wood, 1986). **Box 42** provides more detail on design-based and model-based sampling.

Purposive sampling entails selecting sample units based on arbitrary factors such as ease of access or particular environmental conditions. Purposive sampling is often associated with intensive monitoring and long-term research projects for which population inference is not an objective. However, if purposive samples are to be used for inferential purposes, model-based rather than design-based methods must be used because the samples lack a basis in randomisation or probabilities of selection.

Box 42: Design-based and model-based sampling

Design-based sampling, also known as probability-based sampling, is a widely-known sampling approach. Population units are selected for the sample using a predetermined random probability-based process. The most frequent examples are:

- simple random sampling, systematic;
- sampling with a randomly selected starting point and preferably a randomly selected orientation; and
- stratified random sampling.

Cluster and double sampling approaches are also common. Every population unit must have a known positive probability of selection into the sample with the randomisation process determining the particular population units selected for the sample. The probabilities are the sole basis for drawing conclusions or inferences usually formulated as probability statements such as confidence intervals. From the sample about the population parameters (e.g. total or mean), proportion of the population with given characteristics such as disturbance or occurrence of a rare species, or variance. Thus, if a sample is selected according to the chosen random design, statistical inference based on these probabilities is valid and estimates do not rely on any assumption about the spatial distribution or other pattern in the population. Apart from measurement and observation errors and allometric model prediction errors, sampling is the only source of stochasticity considered and the effects of this uncertainty can be estimated. NFIs typically use probability-based sampling designs with systematic components such as plots established on systematic grids or randomly within regular tessellations of the population where the probability of selection for each plot is equal, positive and known. Probability sampling designs do not preclude unequal probabilities of selection into the sample. Examples include stratified sampling with different stratum-level sampling intensities, sampling proportional to size (e.g. point sampling or variable radius sampling) or proportional to a prediction (e.g. estimated volume or height as in Probability Proportional to Prediction (3P) sampling).

Model-based inference hypothesises a model that relates the response (Y, or dependent) variable of interest to one or more predictor (X, or independent) variables. A sample is drawn, the model is fit to the sample data, and the model with the sample-based parameter estimates is applied to each population unit. 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, after which mean biomass per unit area for the forest could be estimated as the mean of the model prediction's overall population units. The unbiasedness of model-based estimators depends on the adequacy of the assumed model and the similarity between the moments of the predictor variables for the sample used to construct the model and moments for the population to which the model is applied. Whereas uncertainty for design-based inference is primarily based on population variability, uncertainty for model-based inference is based primarily on the uncertainty in the model parameter estimates, the residual uncertainty around model predictions, and spatial correlation among the residuals.

Sample size considerations

To select a ground sample, the first step is to determine the sample size, which may be predetermined due to factors such as available budget and/or required precision. The sample size must be sufficient to capture the variability in the population and to make it likely that the accuracy and precision of estimates of population means satisfy their intended purposes. For probability sampling, a predetermined estimate of the sample size necessary to achieve the desired precision is made. 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 percent as a default at the 95 percent confidence interval. For simple random or systematic sampling of the population, or of a stratum within the population, the estimated sample size required is:

Equation 60

$$n = \frac{t^2\sigma^2}{P^2}$$

where CV is the expected coefficient of variation expressed as a percentage and calculated as the ratio of either the sample standard deviation or a model residual standard deviation and the sample mean; P is the ratio of the desired confidence interval half-width and the sample mean, also expressed as a percentage of the mean; and t is taken from the t distribution with n-q degrees of freedom, where q is the number of parameters estimated, at the desired confidence level, commonly 0.05 which corresponds to a 95 percent confidence interval. Sample sizes to detect rare occurrences such as deforestation may need to be relatively large when using simple random sampling. For example, assuming simple random sampling, sample sizes of $n > 300$ may be required if expected areas of annual forest disturbance are in the order of only 1 percent of the population area. Stratified sampling can be used to substantially reduce required sample sizes.

For model-based sampling, preliminary estimates of the model parameter estimates based on previous studies or expert knowledge are used to guide sample selection. In statistics, model-based sampling is often characterised as optimal design (Silvey, 1980; O'Brien and Funk, 2003).

Supplementary sampling

Supplementary sampling may be necessary when data acquired from a plot-based sampling program such as an NFI do not produce satisfactory results. A common example is insufficient precision for the estimate of a population parameter, particularly a change parameter that the original sampling was not specifically designed to estimate. In addition, the sample may need to be extended to new areas. Examples relate to the necessity of extending the original sample to lands originally excluded due to factors such as ownership criteria or different definitions of forest land. If design-based estimators are to be used, caution must be exercised when selecting additional sample units to ensure that the augmented sample retains its probability features.

A solution that can be easily implemented, regardless of the original sampling design, is to select an entirely new probability sample, calculate estimates for each sample separately, and then combine the estimates by weighting the two estimates, perhaps by the inverses of their respective variance estimates. Of importance, the sampling design for the augmentation sample does not necessarily have to be the same design as for the original sample, although it must be a probability sample.

An original simple random sample can easily be augmented by simply randomly selecting additional sample units within the existing population. Within an extension of the population to new areas, the same sampling intensity used for the original population can be used for the new areas. For stratified random sampling with simple random sampling within strata, insufficient precision can be remedied by additional simple random sampling within strata. For extension of a stratified sample to new areas, a relatively easy solution is simply to define the new area as an additional stratum. Attempts to augment a stratified sample with different within-stratum sampling intensities using a different augmentation stratification should be avoided. For this case, supplementary sampling would most likely need to be tailored individually for new strata defined by the intersections of the original and augmentation stratifications. The result may be a large number of new strata, some of which may be quite small, but all of which will require an adequate sample size.

Several methods for augmenting an original systematic sample to increase precision can be used. Assuming that a grid is used, the grid spacing in one or both directions can be reduced. Or, if plot locations were originally selected within regular polygons, additional plots can be selected within the polygons. If the resulting sample size is then too large, a systematic sample of the new plot locations can be selected, although the resulting sample may not be exactly spatially systematic. Methods for extending an original systematic sample to new areas depend on the nature of the new areas. If the new area is wholly contained within the spatial boundaries of the original population, grid-based plot locations that were originally excluded can simply be included. If the new area is external to the spatial boundaries of the original population, the grid can simply be extended to the new area.

If the design-based, model-assisted estimator or the model-based estimator is to be used, a purposive sample may be selected to enhance model features, such as prediction accuracy at the extremes of the ranges of the independent variables. The combined original and purposive sample can be used to construct the model for both model-assisted and model-based inference. However, although the combined sample can be used to assess uncertainty for model-based inference, only the original probability sample can be used to estimate the model-assisted population mean and its variance.

Additional considerations when constructing inferences for the target population

Where population parameters are estimated from the sum of subsamples or separate models or relationships, double counting of pools must be avoided. All sources of uncertainty must, as far as possible, be identified, and their effects estimated. These include sampling variability, observation and measurement errors, and model prediction uncertainty.

To achieve the desired sampling and modelling objectives, stratification by climate (rainfall, temperature) or broad environmental conditions (altitude, topography, soil type), possibly integrated into bio-geo-climatic zones, is often necessary. 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, plus allow the estimation of the components of change: in growth, accretion, mortality and removals. 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 population is redefined 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 the current condition more accurately. 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 is replaced each measurement period has been used in the past as a compromise to estimating change and current condition, but has generally been found to be a complex compromise and difficult to maintain (Kohl, *et al.*, 2015)

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Appendix B Relative Efficiencies

This appendix contains the results and the literature references supporting the conclusions summarised in **Section 3.1.4**, **Box 26**.

Table 29: Relative efficiency of using the national versus UMD GFC based F/NF and change maps for Gabon

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	49.7
UMD GFC tree cover with 30% cover threshold F/NF no MMU map	Tropical rainforest	Net forest change area	2.6	61
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

Type of reference data: independent interpretation of satellite imagery.

Table 30: Relative efficiency of using the national and UMD GFC based F/NF and change maps against sample data for Gabon

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
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

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	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

Type of reference data: independent interpretation of satellite imagery.

Table 31: Relative efficiency of using the national and UMD GFC based F/NF against sample data for Tanzania

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%
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	50%
UMD global map (tree cover). Calibrated to local forest definition.	Miombo woodlands	Forest area	1.8	44%
RapidEye optical satellite images. Calibrated to local forest definition.	Miombo woodlands	Forest area	1.7	41%

Type of reference data: National inventory of ground plots (first 6 cases; photo interpretation of visual images (cases 7 and 8).

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Appendix C Early Warning Systems

Satellite-based forest monitoring has become an integral part of REDD+ monitoring, but most assessments are done on an annual or biennial basis and only detect forest changes well after it has occurred. Beyond monitoring historical land cover changes, satellite-based monitoring can also play a role in informing emission reduction interventions through the use of near-real-time Early Warning (EW) systems that detect forest cover loss daily, weekly or monthly. The frequency and low latency of EW systems makes it possible to respond rapidly to deforestation events, potentially halting further clearing of forest.

Despite the fact that EW systems and REDD+ monitoring and reporting can both be part of a country's National Forest Monitoring System and may both rely on satellite imagery, EW systems typically have a number of differences from MRV systems:

- **Objectives -** The most fundamental difference between EW systems and MRV is that EW systems are built as a tool for assessing deforestation rapidly in order to form a response action, rather than any reporting obligation. This results in many implications for the properties listed below.
- **Sensors -** Baselines and historical data are generally less important for EW systems compared with MRV, since the most important data from EW systems concern what has happened recently. This means that newer sensors, such as from the European Copernicus program, may be easier to use for EW than as part of MRV. Instead, the frequency of observation is key, as it allows for more rapid detection of forest disturbance. EW systems often benefit from radar data (or radar in combination with optical data), since clouds and smoke which often limit the frequency of optical sensors in the tropics do not affect microwave (radar) signals.
- **Methods -** EW systems often take advantage of the full temporal detail of time series data, which is helpful for accurate forest cover loss detection. Methodologies vary, but may use a probabilistic approach to enable the inclusion of data streams from several sensors. The probability thresholds at which deforestation is flagged can be set to change the likelihood of commission or omission errors, according to stakeholder needs. For example, some stakeholders that are responding to EW alerts over extensive areas may have a very low tolerance for commission errors, due to the high cost of field interventions (at the expense of higher omissions). Those that conduct regular patrols of smaller areas, say a national park, may be able to tolerate a higher level of false positives in order to reduce omission. Although methods to pre-process data from many sensors are well developed, there are still some remaining challenges, particularly for the newer data streams. Several steps should be taken to combine data from different sensors, including co-registration. In seasonal forests, spatial normalisation is commonly used to account for seasonal effects on the time series. Reference data (ground data, or fine resolution optical images) are often used to calibrate and assess the accuracy of such systems (Reiche *et al.*, 2018). In many cases, a forest mask is applied in order to reduce commission errors from non-forest areas (Sano *et al.*, 2019). Different forest masks (with different definitions) can potentially be applied by the users. Automation is also often needed for EW systems to ensure regular, on-time data updates. At a minimum, manual updates to EW systems should have sufficient staff and priority level to achieve continuous operation.
- **Accounting / reporting requirements -** EW systems do not face the same set of rules and requirements as MRV systems. Instead, EW systems should be built according to the needs of the target stakeholders. Rules for accurately accounting for area estimates (Activity Data) do not apply, since the objective is to detect forest disturbance rapidly rather than accurately estimate its extent. Likewise, the accuracy of the system should be tuned according to stakeholder needs,

rather than any requirement (Reiche *et al.*, 2018). Countries are under no obligation to create their own EW monitoring systems and can use existing global or private systems as a tool if they like.

- **Update cycle -** While MRV data are usually generated according to reporting cycles, EW systems are more likely to be provided continuously, as soon as new alerts are generated, to allow for quick responses to the detected forest disturbances. Many alert systems update on daily, weekly, biweekly or monthly cycles.
- **Thematic detail -** EW systems are typically limited to forest cover loss, rather than carbon emissions, as it is unclear how emission information would improve follow-up actions. Further information is generally required to assess if the loss event is anthropogenic, illegal, and/or requires further action. Auxiliary data (e.g. protected area and concession boundaries) can often help with this step. Some also use fine resolution, high-frequency satellite imagery to verify EW alerts and provide additional context on their drivers. Some commercial systems provide screening/prioritisation of EW alerts to users based on certain criteria, and several countries have developed their own methods to prioritise follow-up action.
- **Stakeholders -** While the stakeholders for MRV systems are often international bodies, EW systems are more typically designed for and delivered to stakeholders within the country who have the capacity to follow up on EW alerts, such as law enforcement agencies, protected area managers, private landowners and on-the-ground civil society organisations.
- **Information flow -** As the objective of EW systems is to provide information for action, the data and information created by an EW system must flow to the appropriate actors for follow-up. Countries working with EW systems must have proper institutional arrangements to allow for data sharing between the agencies creating the system and those acting on it. Public availability of the information created by EW systems can also be helpful, to encourage the use by landowners, civil society, and other actors.
- **Response -** To be effective, EW systems should result in follow-up action when illegal deforestation is detected. The exact actions taken will vary by context, but may include conducting an on-the-ground operation, filing a formal legal complaint, destroying the equipment used to deforest land, or fining the perpetrator.

Given these differences, an EW system cannot replace an MRV system, and vice versa. Often, both are required to meet the needs of the relevant stakeholders.

Several countries have now created or are using EW systems to discover and act upon illegal deforestation. For example, the National Program for the Conservation of Forests for Climate Change Mitigation (PNCBMCC) in Peru's Ministry of Environment began adopting deforestation alerts from global systems starting in 2015, and in 2018, began operating its own EW system (Vargas *et al.*, 2019). The case from Peru demonstrates several of the EW system properties outlined above:

- **Objectives -** PNCBMCC already had an MRV system in place in 2015 for reporting, but also wanted an EW system in order to regularly assess deforestation within project sites of its Direct Conditional Transfer program with indigenous communities. Since building the system, it has also increased collaboration with the parks service and regional environmental prosecutors, who are using the information to identify potential illegal deforestation on a regular basis in order to apply legal remedies.
- **Sensors -** At the moment, Peru uses Landsat for both its MRV system and its EW system. However, PNCBMCC is also experimenting with radar sensors such as ALOS-2 PALSAR-2 for its EW system, because cloud cover often results in delays in deforestation detection in the Amazon using optical imagery.

- **Methods -** The EW system uses a Direct Spectral Unmixing approach that is similar to that of Peru's annual forest cover loss monitoring (Vargas *et al.*, 2019). However, the EW system approach is less rigorous, for example in the detection of cloud cover, and in post-processing removal of errors.

- **Accounting / reporting requirements -** PNCBMCC originally used global EW systems, GLAD and JJ-FAST, for near-real-time monitoring, as there were no requirements about country ownership. Then, when it had proved the utility of EW and had a clear idea of what it wanted to improve, it developed it's own system that is more attuned to the local context, for example, better detecting forest roads, reducing false positives in flooded areas, and better detecting smaller deforestation patches.

- **Update cycle -** Peru's Activity Data for MRV is updated on an annual basis, with some manual post-processing steps. Meanwhile, the EW alerts are updated semi-automatically on a weekly basis.

- **Thematic detail -** The EW system only captures humid tropical forest loss. PNCBMCC also provides additional data layers on its publicly available Geobosques web platform, such as recent satellite imagery and boundaries of protected areas and concessions, to assist users in prioritising alerts. In addition, it also provides more detailed reports, with before and after images to partner agencies for particular areas of interest, such as protected areas.

- **Stakeholders -** The alerts were of key interest to the PNCBMCC's own Direct Conditional Transfers program, which rewards indigenous communities for conserving forests in their territories. The alerts are also regularly used by Peru's Protected Areas Service and Environmental Prosecutor's Office, as well as by civil society organisations and communities, who access the alerts through the Geobosques platform.

- **Information flow -** PNCBMCC has sought to make the alerts readily available and accessible to the public through its Geobosques platform, which allows users to view and download the data, as well as sign up for notifications of new alerts in their area of interest. The Ministry provides regular training on the platform, with a focus on staff within Peru's Protected Area Service and Environmental Prosecutor's Office. The team also creates more detailed reports with before and after images for particular areas of interest, such as protected areas, or particularly large clearings, which are sent to the relevant authority.

- **Response -** For their Direct Conditional Transfers program, communities are requested to provide a field report for any alerts detected within their conservation area. If it is determined that the community violated their agreement, they may be dropped from the program. The Protected Area Service also regularly uses alerts to help plan patrols and identify potential areas of illegal activity. If they find evidence of illegality, they may destroy equipment and involve the Environmental Prosecutor's office. Many other civil society organisations in Peru use these alerts and those from global systems to prioritise patrol efforts, provide additional evidence of illegality in legal complaints, and expose illegal deforestation.

More information about EW alerts in Peru, as well as the successes and challenges faced in their use, is available in Weisse *et al.*, 2019.

For those countries looking to explore early warning systems, several pantropical EW systems already exist and are publicly available, including: **GLAD alerts** from the University of Maryland and Global Forest Watch (Hansen *et al.*, 2016), **Terra-i** from the International Center for Tropical Agriculture (Reymondin *et al.*, 2012), and the radar-based **JJ-FAST** from the Japan International Cooperation Agency (JICA) and the Japan Aerospace Exploration Agency (JAXA). In addition, tools such as SEPAL and Google Earth Engine include functionality and modules for creating EW systems. A number of national governments in the tropics operate their own EW systems, such as in Brazil (Diniz *et al.*, 2015), Peru (Vargas *et al.*, 2019), Colombia, and Ecuador.

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Global Forest Observations Initiative Programme Office
Food and Agriculture Organization of the United Nations
Headquarters
Viale delle Terme di Caracalla
00153 Rome, Italy
Email: office@gfoi.org

www.gfoi.org