Review of Priority Research & Development Topics

R&D related to the use of Remote Sensing in National Forest Monitoring

Version 1.0

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Global Forest Observations Initiative
%GEO, 7 bis, avenue de la Paix,
Case postale 2300
CH-1211, Geneva 2,
Switzerland
office@gfoi.org

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EXECUTIVE SUMMARY

The GFOI Research and Development (R&D) Component focuses on improving remote sensing data inputs and derived map products in order to help enhance the functionality and accuracy of National Forest Monitoring Systems (NFMS). NFMS may serve UNFCCC greenhouse gas emissions reporting requirements, as well as supporting broader environmental monitoring needs. This Component incorporates the R&D needs identified directly by GFOI countries, and of key GFOI partners such as the FAO and the World Bank, as well as research bodies supporting the further development of global forest monitoring programs. It covers a focused R&D action addressing immediate needs by countries, rather than long-term, more speculative or blue-sky research activities in the forest monitoring domain.

The Global Forest Observations Initiative (GFOI) was set up by the Group on Earth Observations (GEO) in 2011, to foster the sustained availability and use of remote sensing data and ground observations in support of national efforts to better manage forest resources. It will achieve this by improving the coordination of satellite data acquisitions and facilitating access by countries to this data; providing advice on operational forest monitoring methodologies; and supporting capacity-development for countries that wish to establish improved forest monitoring systems in accordance with the IPCC Guidelines. GFOI builds upon the GEO task on Forest Carbon Tracking (FCT), which, since 2008, established several *National Demonstrator Countries* (NDs) to conduct initial tests and demonstrations on the use of satellite earth observation data for forest monitoring.

From the start, GEO FCT and GFOI have encouraged countries to focus on development of systems that use wall-to-wall, time-series satellite data across several years, and that cover the full national territory. This provides better tracking of the longer-term trends in forest cover, helps avoid issues of leakage, and helps countries demonstrate persistent and positive long-term national-level emissions reduction outcomes arising from legislation, policy or finance mechanisms. Therefore the GFOI R&D Component focuses on helping countries establish robust long-term forest monitoring systems through better ways to use multiple, complimentary remote sensing and earth observation data sources, to help fill data gaps and construct long times series of satellite observations. In addition, the component will include projects that cover R&D on improved, practical forest measurement techniques, and data-model integration methodologies that enhance the functionality and/or accuracy of emissions reporting systems.

Other parts of GFOI are also supporting national forest monitoring through the capacity-enhancement, and through these country contracts it is recognised that several R&D needs related to remote sensing exist, in particular around the combination and use of multiple satellite data sources for time-series, wall-to-wall mapping or gap-filling, or mapping of specific, unique land-cover types. The research needs have been prioritised to highlight those that are most urgently needed by countries to implement practical national forest monitoring systems that comply with the IPCC Good Practice Guidance [1], [2] and are sustainable and affordable. The review also identifies current gaps and opportunities for improving forest monitoring systems, with newly available earth observation technologies or ground-based measurement methods, which show promise in contributing to further improvement of current operational forest monitoring. This document also provides a useful reference on the latest forest monitoring techniques being developed worldwide and their level of operational readiness.

This document has been widely reviewed and will form the basis of a research programme to improve national forest monitoring systems.

The GFOI R&D Strategy is being developed in parallel with the Methods and Guidance Documentation (MGD) [3].The GFOI MGD is intended to be of use in developing NFMS

consistent with UNFCCC decisions, the IPCC Guidelines and the GOFC-GOLD Sourcebook [54]. This document is part of GFOI's attempt to ensure that, in the future, it is possible to provide universal advice that would enable all countries to implement national forest monitoring systems and solid continuous improvement R&D programs. R&D is already underway on some topics ranging from academic research to more practical applied studies in countries trying to implement national forest monitoring systems. GFOI will aim to complement these activities by promoting R&D that fills gaps in the existing work.

The following steps are envisaged:

- The GFOI office will assume a coordination role for the GFOI R&D component.
- A GFOI Science Panel will be created to provide scientific and technical guidance to the GFOI office and to the R&D projects as well as assessing the R&D outcomes.
- GFOI will consult with potential partners on these R&D needs and discuss the development of specific R&D proposals and how they can be implemented.
- The R&D results should be sustainable (i.e., repeatable in the longer term using available data), practical and widely adoptable. It is expected that their outcomes will be incorporated into future versions of the GFOI Methods and Guidance Documentation. All outputs will be widely and freely distributed.
- This review will be updated on an annual basis, with on-going inputs from GFOI countries and their partners, as they work to establish such forest monitoring systems.

GFOI Forest Map Products

This review covers those remote sensing-derived forest map products needed by countries as they establish their national forest monitoring systems as shown in Tables 1 and 2 below deciding if they are already operational, if they are pre-operational or are still in a research (R&D) Phase, and considering what additional R&D is needed to improve them.

In general, GFOI considers the following criteria, in order to define remote-sensing derived products to be operational, pre-operational or R&D in this document:

Operational[1]:

- Core satellite data is available for baseline mapping and time-series analysis at relevant resolution and repeatability.
- Long-term continuity of existing EO data streams.
- Data-processing methods have been documented in peer reviewed publications.
- Production system already implemented in some countries as part of national environmental and forest monitoring programs, or demonstrated at sub-national scale.
- Processing workflows and systems are robust and repeatable.
- Methods have ideally been demonstrated to be applicable in sub/tropical forest monitoring contexts.

Pre-operational[2]:

- Data processing methods have been documented in peer review publications.
- Methods have ideally been demonstrated to be applicable in sub/tropical forest monitoring contexts.

[1] It is recognised that although a product may be operational there may be limits to its applicability, e.g., operational optical techniques have difficulties where there is persistent cloud cover.

[2] Includes some techniques that are pre-operational now but are likely to be operational when the data becomes available, e.g., SAR-based monitoring for which satellites will be launched in 6-12 months.

- Basic satellite data may not necessarily yet be available for routine baseline monitoring and time-series analysis.
- Processing workflows and systems require implementation in larger-scale processing systems or national monitoring programs.
- Long-term continuity and future EO data is somewhat uncertain.

Research (R&D):

- Mapping methods may have been demonstrated over large areas.
- The methodology still needs to be tested as repeatable or applicable in a sub/tropical environment.
- Promising case studies exists, and help identify the extent to which additional R&D is needed to advance the methodology to operational status.

Note: *In some cases, data availability for some data types is such that operational status is reached (e.g., with multispectral optical data), but is not yet available for other datasets (e.g., SAR). At the time of writing of this document, a number of new SAR satellite systems are 6-12 months away from launch, meaning that pre-operational SAR-based mapping methods could quickly be transitioned by countries to more operational processing mode.*

The GFOI Methods and Guidance Documentation [3] defines seven thematic forest map products, derived from satellite remote sensing data, and their general specifications (Table 1), that GFOI will support through facilitating improved access to relevant satellite data, as well as through key methodological guidance preproduction of these products. This will enable countries to routinely and precisely measure Forest Area Change and Carbon Stock Change estimates. In addition, GFOI has identified four supplementary forest map products that should be useful for NFMS and REDD+ reporting in the future if R&D is successful (Table 2).The product specifications are inherently flexible to accommodate national definitions and uses other than GHG emissions reporting. The Minimum Mapping Unit (MMU) and Temporal Production Frequency items are included as a guide only, they are not a REDD+ requirement, but are technically feasible given suitable remote sensing data.

Countries will not necessarily need to produce and use all of these products. Typically requirements will depend on monitoring needs and will be greater the more activities are to be monitored, e.g., within the REDD+ spectrum of deforestation, forest degradation, sustainable management of forests and conservation. Countries may start with Forest/Non-forest and change products to monitor their forests and move to using Forest stratification and All Land use categories and change products to increase accuracy and integrate with wider national monitoring as capacity and resources permit.

It should be reiterated that these map products are not end products; rather they represent intermediate information and inputs used for greenhouse-gas emissions estimation that provide improved confidence intervals for country emissions estimates. Their possible use is described in the Methods and Guidance Documentation [3].

Table 1. GFOI Recommended Forest Map Product Specifications [3]					
Map number	**Map Name**	**Purpose**	**Description/Comment (Operational status[3])**	**Minimum Mapping Unit**	**Temporal Production Frequency**
1)	Forest/Non-forest	Visual appreciation of trends for policy purposes; basis for other products[a]	Maps of forest cover through time (Operational[4])	< 0.5 ha	Annual
2)	Forest/Non-forest change	Activity data for deforestation and increase in forest area expressed on an hectare or percentage	Maps of change in the area of forest land[b] (Operational[4])	< 0.5 ha	Annual
3)	Forest stratification	Visual appreciation of forest resources; basis for other products[a]	As map 1, but with forest stratified according to PF, MNF, PlantF (or equivalent national stratification) and any sub-stratifications (Operational[5])	< 0.5 ha	Annual
4)	All Land use categories	Visual appreciation of national land use; basis for other products[a]	Default is UN-FAO Land Cover Classification (LCCS) or an equivalent national classification, and allowing aggregation into the six IPCC Land Categories. Forest included using Forest/Non-forest maps, stratified as in map 3 (Operational[6])	< 0.5 ha	Annual
5)	Land use change between forests and other land uses	Activity data for deforestation and for enhancement of forest carbon stocks by afforestation or reforestation; activity data if needed for non-forest LULUCF activities	Maps of conversions between the six IPCC Land Categories, with forest stratified as described in 3) and 4) (Operational[6])	< 0.5 ha	Annual
6)	Change within Forest land	Activity data for degradation, sustainable management of forests, enhancement of forest carbon stocks within forest remaining forest, and conservation	Maps of conversions between forest strata described in 3), and of on-going activities such as harvesting within categories (Operational[5])	< 0.5 ha	Annual
7)	Near-Real Time Forest Change Indicators	Early warning of deforestation and degradation	Not needed for measurement of emissions, but useful for early warning and detection of forest clearing and degradation, and so may be needed as part of the implementation of REDD+ (Operational[7])	> 0.5 ha	Bi-monthly or better

[a] Consistent with Guiding Principle 1, it is the underlying images used to produce this product that are the basis for other products, not the map itself.

[b] May be necessary to use supplementary ground-based data if there are significant harvested areas awaiting restocking.

[3] See the GFOI working definitions of Operational, Pre-operational and R&D above.

[4] Product considered operational for key optical datasets and L-band SAR, however still in R&D phase for C-band SAR.

[5] Product considered operational for key optical datasets when stratification is limited between primary forest (PF) and planted forest (PlantF), but pre-operational if distinguishing between several sub-strata of natural forest. Product still considered in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

[6] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively. Annual mapping of All Land use categories and change at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories.

[7] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

Table 2. GFOI Supplementary Forest Map Product Specifications

Map number	Map Name	Purpose	Description/Comment (Operational status[3])	Minimum Mapping Unit	Temporal Production Frequency
8)	Degradation Type Map	For detail on degradation and higher accuracy when calculating emissions	Map of forest degradation types and proxies/indicators of degradation (R&D).	> 0.5 ha	Every 5 years
9)	Degradation/Enhancement of C stocks	Degradation/Enhancement activity data	Mapping of biomass/carbon loss or gain, or change in other vegetation metric relative to a reference year (R&D)	< 0.5 ha	Annual
10)	Above-Ground Biomass (AGB) Estimation	Above-Ground Biomass (AGB) estimation	Map showing vegetation biomass estimates that can be used in IPCC reporting following the IPCC Guidelines (R&D).	> 0.5 ha	Every 5 years
11)	Change in Above-Ground Biomass (AGB)	Change in Above-Ground Biomass (AGB)	Map showing changes in vegetation biomass estimates that can be used in IPCC reporting following the IPCC Guidelines (R&D).	> 0.5 ha	Every 5 years

[3] See the GFOI working definitions of Operational, Pre-operational and R&D above.

This Review

This review(Chapter 2 and 3 with full details in Annex B) attempts to clarify the current state of operational readiness with regard to each of the GFOI Forest Map Product specifications mentioned above. The extent to which each of the products can be generated today is assessed. The review considers the maturity of the technology, and whether the derived information products are used operationally or pre-operationally by countries. Promising case studies help identify the extent to which additional R&D is needed to advance the methodology to operational status. "Operational readiness" naturally also relates to access to relevant satellite data, preferably in a free and open manner, plus the level of assurance that space agencies are able to give in terms of continuity of these data streams into the next 5 – 10 years. The current and near-future availability of publicly free and open satellite data, here referred to as "GFOI core" data (including e.g., Landsat-7 and -8, Sentinel-1 and -2, CBERS-4), and commercial satellite data, here called "non-core" (e.g., RapidEye, SPOT, IRS, RADARSAT-2, TerraSAR-X/TanDEM-X) data streams is considered. Reference to the GOFC-GOLD Sourcebook [54] is made in relation to methods and data requirements relevant to the product specifications.

Priority R&D

The R&D Programme of GFOI aims to help improve current operational methods and data, and so move map products from an R&D phase to pre-operational, and then let countries implement the new methods and/or datasets into their operational systems. The review identifies what R&D is required in order to make a product pre-operational and to improve the accuracy and reliability of each product. The full list of R&D Topics identified is given in Table 3 below. The highest priority topics are those that address immediate data needs. Thus topics that address time series consistency, accuracy and stratification according to national requirements are the highest priority, while newer techniques such as biomass estimation from aircraft and satellites is currently a lower priority although, in the future, this may change as these newer techniques mature. Two factors have been used to prioritise the R&D topics: the "perceived forest country needs", described in Chapter 3 and the inventory considerations discussed in Section 4.1. It is assumed that

- it is most important to address the topics identified in Section 4.1: time series consistency (*note – TSC is considered a broader GFOI capacity enhancement issue and is not addressed in the R&D Plan – refer to Annex C*) and forest stratification;
- the R&D programme should concentrate on improving those products that are considered useful for a basic national forest monitoring system (comprising remote sensing and ground data), and those considered non-operational, either due to lack of regular or cost-effective data access issues, or insufficient application across different regions and forest types;
- Forest stratification is a minimum requirement and considered a higher priority than Forest/Non-forest and Forest/Non-forest change products;
- forest degradation products are considered important as this has been identified by users as a gap in the existing data provision;
- methodology development should initially focus on using data from GFOI core missions (e.g., Landsat-8, Sentinel), both independently and interoperably.

Table 3. Research Topics Identified in this Review		
Topic		**Priority**
General forest mapping method improvements	Sensor interoperability - Generating similar thematic products from different sensor systems for assembly of time-series	**HIGH**
	Sensor complementarity for improved information extraction and monitoring	
	Uncertainty and inference	
	Assess potential generation of products using simulated future datasets such as (i) Sentinel-1/RCM time-series, (ii) Sentinel-2, and (iii) Hyperspectral (EnMAP) data	
	Optimising information extraction using dense time-series C-band SAR	
Data-Model integration	Improved ground data and soil carbon budget models for new forested areas (e.g., peat soils)	
Land use change	Exploitation of SAR texture and polarimetry for greater class separability	
	Sensor interoperability and complementarity for improved detection and mapping of land use change	
	Use of VHR data for calibration/validation of change products	
Forest stratification	SAR texture metrics and polarimetry	
	Sampling and species distribution models	
	Consistent methods across biomes	
	Airborne LiDAR or InSAR structural classification	
	Forest type mapping from simulated future hyperspectral data	
Degradation/Enhancement of C stocks	Mapping methods for regrowth	
	Proxy, quantitative measures of degradation	
	Deriving forest degradation products and field validation from VHR data	
	Use of SAR data for mapping degradation	
	Use of airborne LiDAR for deriving biomass/carbon stocks and change	
	Assessment of the relationship among definitions of degradation, degree of degradation that can be detected, associated accuracies, and useful kinds of remotely sensed data	
All Land use categories	Further exploitation of SAR for mapping land use categories	**MEDIUM**
	Identify data needs and methods for evaluation of global product accuracy	
F/NF mapping	Investigate alternative non-GFOI data streams for F/NF mapping	
Forest/Non-forest change mapping	Improved methods for burned area mapping	
	Optimising F/NFchange mapping using dense time-series C-band SAR	
Near-Real Time forest change indicators mapping	Test different spectral fractions to identify disturbance pixels in different forest types and regions	
	Investigate alternative non-GFOI data streams, such as TerraSAR-X and future ALOS-2 ScanSAR	
	Methods and data for validation of products	
	Exploiting dense time-series C-band SAR	
Degradation Type mapping	Methods of extracting land use history (e.g., forest type and age, land use transitions following clearing/re-clearing) from optical time-series	
	Automated mapping methods	
	Use of fractional cover and evaluate different spectral indices	
	Evaluate different change detection approaches	
Above-Ground Biomass estimation	Biomass stock stratification approaches (design- and model-based)	**LOW**
	Link between AGB and other carbon pools (e.g., soil carbon)	
	R&D to generate more data for GlobAllomeTree tool	
	Transferability of methods from boreal to temperate to tropical forest	
	Airborne LiDAR or SAR tree height correction	
	Bi-static SAR for estimating tree height	
	Integration of ground,- and airborne LiDAR, SAR and optical data	
	Integration of LiDAR and optical data for calculating past emissions	
Change in Above-Ground Biomass	Modelling approaches using repeat LiDAR	
	Integration of repeat LiDAR and SAR to estimate biomass change across different forest types	
	Sampling design options	
	Transferability of methods to tropical biome	
Socio-economic analysis	Drivers and change and impact on GHG emissions	
	Link between EO data to enhance village livelihoods	

In the course of this review, a number of additional country needs were identified that go beyond R&D. These include capacity building, data supply and institutional issues. They are listed in Table 4 below. Notable issues are addressed in Annex C.

Table 4. Other Country Needs Identified in this Review

	Topic
General assistance with implementing forest mapping method improvements	Hyper-temporal processing
	Spatio-temporal data mining techniques
	Cloud-free compositing
	Standardised method of identifying reference levels against which countries can quantify carbon stock changes due to degradation (including use of stable ground sites and remote sensing data)
	Country specific land use change transition classes
	Improved computational efficiency of integrated remote sensing data, in situ measurements and models for carbon stock estimation and emissions reporting
	Mapping seasonal land cover dynamics using SAR data
Improving data access	High resolution DEM (TanDEM-X or 30 m SRTM)
	Ensure on-going access to Landsat-like data, or alternative data sources/methods that comply with existing programs
Institutional frameworks	Set-up and design of NFMS and NFI
	Open source software
	Cloud computing opportunities
	Capacity enhancement

Table 5 indicates priority R&D topics. The highest priority is to address Time Series Consistency, Satellite Sensor Interoperability and Stratification for the Land use change between forests and other land uses, Forest stratification and Degradation and/or Enhancement of C stocks products, as well as and Proxy Methods for the Degradation and/or Enhancement of C stocks product.

Table 5. GFOI Priority R&D topics: Approaches and issues for consideration

(yellow highlights products that are high priority,
and ✖ indicates topics that address priority issues and × are other R&D topics)

GFOI Product	Time Series Consistency	Hyper-temporal Processing	Spatio-temporal data mining	Satellite Sensor Interoperability	Stratification	Proxy Methods	Software Development & Capacity Building	Uncertainty &Inference	Data-Model Integration	Socio-economic Analysis	Overall Inventory priority	Operational Readiness
1) Forest/Non-forest	✖			✖							**Medium**	**Operational[4]**
2) Forest/Non-forest change	✖	×	×	✖			×	×	×	×	**Medium**	**Operational[4]**
3) Forest stratification				✖					×		**High**	**Operational[5]**
4) All Land use categories	✖			✖							**Medium**	**Operational[6]**
5) Land use change between forests and other land uses	✖	×	×	✖	✖		×	×	×	×	**High**	**Operational[6]**
6) Change within Forest land	✖	×	×	✖	✖			×	×		**High**	**Operational[5]**
7) Near-Real Time Forest Change Indicators	✖	×	×					×		×	**Medium**	**Operational[7]**
8) Degradation type map	✖	×	×	✖		✖					**Medium**	**R&D Topic**
9) Degradation and/or Enhancement of C stocks	✖	×	×	✖	✖	✖	×	×	×	×	**High**	**R&D Topic**
10) Above-ground Biomass Estimates				✖	✖			×	×		**Low**	**R&D Topic**
11) Change in Above-ground Biomass				✖	✖			×	×		**Low**	**R&D Topic**
Tropic Forest Country request	✖	×		✖		✖	×	×				

[4] Product considered operational for key optical datasets and L-band SAR, however still in R&D phase for C-band SAR.

[5] Product considered operational for key optical datasets when stratification is limited between primary forest (PF) and planted forest (PlantF), but pre-operational if distinguishing between several sub-strata of natural forest. Product still considered in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

[6] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively. Annual mapping of All Land use categories and change at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories.

[7] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

1 CONTEXT

1.1 *Document scope*

This document reviews the potential of the various remote sensing-derived forest map products that can be used in implementing and improving national forest monitoring systems[8] and help meet the requirements of the IPCC Guidelines[9] [1]; [2]. It identifies any research and development topics that need to be addressed to ensure that these products can be widely used by forest countries around the world.

The Global Forest Observations Initiative (GFOI) aims to facilitate the supply and use of earth observation information, so that all countries can better manage their forest resources. Initially GFOI aims to support countries' national forest monitoring systems in accordance with the IPCC Guidelines such as the systems needed to implement the United National Framework Convention on Climate Change (UNFCCC) programme on REDD+ (reducing emissions from deforestation; forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks).

GFOI was set up by the Group on Earth Observations (GEO) and has the active support and involvement of 13 space agencies (and data providers). It has been explicitly endorsed by 90 countries plus the EU and 67 international organisations. GFOI engages and coordinates with key organisations and institutions such as the UNFCCC, FAO, World Bank and IPCC as well as developing country participants. GFOI developed from the GEO Forest Carbon Tracking project which successfully demonstrated its approach through selected national demonstrator countries and which started in 2008.GFOI has identified a list of thematic forest map product specifications (see next section) that can be derived from a combination of Earth Observation and ground measurement data, and that are needed for countries to measure and report their changes in carbon stocks in forests and the subsequent greenhouse emissions. A country may not need to use all of these products: their choice will depend on their national circumstances and the additional objectives they have. This review considers these products and for each determines what, if any, additional research and development may be needed before the products can be widely used and recommended for use in long term systematic forest monitoring. These R&D topics are then prioritised by both needs expressed by countries and by the IPCC´s Greenhouse Gas (GHG) inventory good practice requirements of transparency, completeness, consistency, comparability and accuracy, as endorsed by the UNFCCC.

The need for forest information may extend beyond NFMS, MRV, and GHGI objectives. Indeed, the nine societal benefit areas of GEO need some type of information about the forests. Information about the status of forest resources is used in forestry operations, natural resource assessment, conservation and reserve planning and illegal logging detection systems. Similar forest map products may be useful for biodiversity initiatives such as GEOBON. The GEO Initiative provides a unique opportunity for coordination of data and information between different sectors. Global Initiatives such as GEO and GEOBON should consult on cross-cutting information needs and the possibility of generating a suite of forest map products that serve different purposes across sectors.

The current report is the first step in the development of a comprehensive R&D Plan. This Plan will be further developed by the GFOI Office, based on inputs from demonstrator countries, interested organisations and relevant research expertise. Priority Research Topics will be presented to donors for funding.

Following this introductory chapter this report contains:

- Chapter 2: *Current State of Operational Readiness*– summary of the review
- Chapter 3: *R&D needs identified by tropical forest countries* – views expressed by forest countries
- Chapter 4: *R&D Topics* – the R&D topics identified and prioritised
- Chapter 5: *Concluding Summary*
- Annexes*: A IPCC Tier and Approach Concepts*

  : B Selected Examples – Full details of the review

  : C *GFOI Capacity Enhancement* – Broader GFOI issues

  : D *References* – Full list of references used in the review

  : E *Acronyms used in R&D Document*.

1.2 *GFOI information requirements – the Forest Map Product Specifications*

The GFOI Methods and Guidance Documentation [3] defines seven thematic forest map products (see Table 6 below), derived from satellite remote sensing data, and their general specifications, that the GFOI will support through facilitating improved access to relevant satellite data, as well as through key methodological guidance preproduction of these products. This will enable countries to routinely and precisely measure Forest Area Change and Carbon Stock Change estimates. The choice of IPCC[10] "Tier" and "Approach" reporting is naturally for countries to adopt, relative to national circumstances and data availability. In addition, GFOI has identified four supplementary forest map products considered useful for NFMS and REDD+ reporting (Table 7).The product specifications are inherently flexible to accommodate national definitions and uses other than GHG emissions reporting. The Minimum Mapping Unit (MMU) and Temporal Production Frequency items are included as a guide only, they are not a REDD+ requirement, but are technically feasible given suitable remote sensing data.

So, countries will not necessarily need to use all of these products. Countries may start with Forest/Non-forest cover and change products to monitor their forests and move to using Forest stratification and All Land use categories and change products to increase accuracy and integrate with wider national monitoring as capacity and resources permit. It should be reiterated that the map products are not end products; rather they represent intermediate information and inputs used for emissions estimation that provide improved confidence intervals for country emission estimates.

Table 6. GFOI Recommended Forest Map Product Specifications [3]					
Map number	**Map Name**	**Purpose**	**Description/Comment (Operational status[3])**	**Minimum Mapping Unit**	**Temporal Production Frequency**
1)	Forest/Non-forest	Visual appreciation of trends for policy purposes; basis for other products[a]	Maps of forest cover through time (Operational[4])	< 0.5 ha	Annual
2)	Forest/Non-forest change	Activity data for deforestation and increase in forest area expressed on an hectare or percentage	Maps of change in the area of forest land[b] (Operational[4])	< 0.5 ha	Annual
3)	Forest stratification	Visual appreciation of forest resources; basis for other products[a]	As map 1, but with forest stratified according to PF, MNF, PlantF (or equivalent national stratification) and any sub-stratifications (Operational[5])	< 0.5 ha	Annual
4)	All Land use categories	Visual appreciation of national land use; basis for other products[a]	Default is UN-FAO Land Cover Classification (LCCS) or an equivalent national classification, and allowing aggregation into the six IPCC Land Categories. Forest included using Forest/Non-forest maps, stratified as in map 3 (Operational[6])	< 0.5 ha	Annual
5)	Land use change between forests and other land uses	Activity data for deforestation and for enhancement of forest carbon stocks by afforestation or reforestation; activity data if needed for non-forest LULUCF activities	Maps of conversions between the six IPCC Land Categories, with forest stratified as described in 3) and 4) (Operational[6])	< 0.5 ha	Annual
6)	Change within Forest land	Activity data for degradation, sustainable management of forests, enhancement of forest carbon stocks within forest remaining forest, and conservation	Maps of conversions between forest strata described in 3), and of on-going activities such as harvesting within categories (Operational[5])	< 0.5 ha	Annual
7)	Near-Real Time Forest Change Indicators	Early warning of deforestation and degradation	Not needed for measurement of emissions, but useful for early warning and detection of forest clearing and degradation, and so may be needed as part of the implementation of REDD+ (Operational[7])	> 0.5 ha	Bi-monthly or better

[a] Consistent with Guiding Principle 1, it is the underlying images used to produce this product that are the basis for other products, not the map itself.

[b] May be necessary to use supplementary ground-based data if there are significant harvested areas awaiting restocking.

[3] See the GFOI working definitions of Operational, Pre-operational and R&D above.

[4] Product considered operational for key optical datasets and L-band SAR, however still in R&D phase for C-band SAR.

[5] Product considered operational for key optical datasets when stratification is limited between primary forest (PF) and planted forest (PlantF), but pre-operational if distinguishing between several sub-strata of natural forest. Product still considered in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

[6] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively. Annual mapping of All Land use categories and change at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories.

[7] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

Table 7. GFOI Supplementary Forest Map Product Specifications

Map number	Map Name	Purpose	Description/Comment (Operational status[3])	Minimum Mapping Unit	Temporal Production Frequency
8)	Degradation Type Map	For detail on degradation and higher accuracy when calculating emissions	Map of forest degradation types and proxies/indicators of degradation (R&D).	> 0.5 ha	Every 5 years
9)	Degradation/Enhancement of C stocks	Degradation/Enhancement activity data	Mapping of biomass/carbon loss or gain, or change in other vegetation metric relative to a reference year (R&D)	< 0.5 ha	Annual
10)	Above-Ground Biomass (AGB) Estimation	Above-Ground Biomass (AGB) estimation	Map showing vegetation biomass estimates that can be used in IPCC reporting following the IPCC Guidelines (R&D).	> 0.5 ha	Every 5 years
11)	Change in Above-Ground Biomass (AGB)	Change in Above-Ground Biomass (AGB)	Map showing changes in vegetation biomass estimates that can be used in IPCC reporting following the IPCC Guidelines (R&D).	> 0.5 ha	Every 5 years

[3] See the GFOI working definitions of Operational, Pre-operational and R&D above.

1.3 *Achieving NFMS, GHGI and REDD+ requirements – using the GFOI Forest Map Products*

The GFOI Methods and Guidance Documentation [3] provides advice on the integration of remote sensing and ground-based observations for better estimation of emisions and removals of greenhouse gases in forests, consistent with IPCC Guidance [1]; [2], and together with the GOFC-GOLD Sourcbook [54], they support national forest monitoring systems (NFMS) and REDD+ reporting. IPCC GHGI methods require forest classification and stratification and the area of each stratum, and are described at three levels of detail, or “Tiers” [3] (refer to Annex A.1). Three approaches to providing Activity Data involving land area are also described (Annex A.2). Remote sensing is considered a valuable source of Activity Data, where calibration of the data processing algorithms still rely on ground-based measurements and/or very high resolution (VHR) data. The MGD [3] identifies seven thematic forest map products which provide intermediate inputs to estimating emissions. GFOI has identified an additional four supplementary forest map products considered useful for NFMS and GHGI.

Broadly, wall-to-wall assessments of forest and land cover change at national scale in support of Tiers 1 – 3 and Approach 3 (spatially explicit) reporting are considered operational using existing remote sensing data.

The basic requirements of a REDD+ system comprise:

i. Deforestation – forest converted to other land use (LU). Need: area converted (activity data) and annual rate of conversion. Involves forest stratification (primary forest, PF, modified natural forest, MNF, and planted forest, PlantF) and biomass carbon densities for each sub-stratum (sourced from NFI/field sampling);
ii. Forest degradation – long term loss of carbon without LU change. Need: annual rate of change in carbon stocks of MNF and PlantF. Involves spatial mapping of disturbance and logging history, NFI/field sampling, forest stratification and activity data;
iii. Enhancement of C stocks – long term gain in C stocks in existing forest, or by converting another LU to forest. Involves forest stratification, identifying boundaries of areas subject to sustainable management/enhancement/conservation, or afforestation, and activity data [3].

While national scale, wall-to-wall forest mapping programs are not strictly required for forest monitoring in sub-national REDD+ projects, the wall-to-wall approaches advocated by GFOI ensure consistent mapping at both national and project-level scales, avoid problems of leakage, and support easier integration of project-based greenhouse gas inventories into national reports. It is possible to operate parts of a REDD+ system at present (i.e., Deforestation) using ground data (sourced from NFI or additional sampling) and EO inputs. In a basic EO forest monitoring system, F/NF, All Land use categories and Change products can be generated routinely using available GFOI core data and at reasonably accuracy. The GFOI R&D programme will focus on improving those products that are considered useful for an initial forest monitoring system and for generation of reference or baseline levels that countries can use. This may include those products considered non-operational, either due to lack of regular or cost-effective data access issues, or insufficient application across different regions and forest types. Lower priority R&D will consider longer term ‘academic’ research to improve products such as AGB and AGB change which may be useful in future advanced forest monitoring systems.

The following sections aim to relate the GFOI forest map products (including an indication of operational readiness and prioritisation of R&D to improve the product) to the information needs for forest monitoring in the context of REDD+.

Deforestation monitoring requires:

- Activity data – uses All Land use categories (operational) and Land use change between forests and other land uses (operational) products. High priority R&D is required to improve the accuracy of the land use change product (e.g., sensor interoperability, uncertainty metrics). Medium priority R&D is required to improve the All Land use categories product. Countries could additionally generate Change within Forest land (operational) and NRT Forest Change Indicators (operational) products. Some countries may need capacity-enhancement in achieving time-series consistency (i.e., cloud-free compositing).
- Forest stratification – requires F/NF (operational) and Forest stratification (operational) products. High priority R&D is required to improve the Forest stratification product. Medium priority R&D is required to improve the F/NF product.
- Biomass carbon densities – from NFI/field sampling or AGB (R&D) and AGB change (R&D) products. High priority R&D is required to improve uncertainty metrics. Low priority R&D is required to improve the AGB and AGB change products.

Degradation monitoring requires:

- Activity data – same as for Deforestation, and including Change within Forest land (operational) product.
- Forest stratification – same as for Deforestation.
- Disturbance history – requires Degradation/Enhancement of C stocks (R&D) and Degradation Type (R&D) products. High priority R&D is required to advance the Degradation/Enhancement product to operational status. Medium priority R&D is required to improve the Degradation Type product.
- Biomass carbon densities – same as for Deforestation.

Enhancement of C stocks monitoring requires:

- Activity data – same as for Deforestation, and including Change within Forest land (operational) product.
- Forest stratification – same as for Deforestation.
- Disturbance history – requires Degradation/Enhancement of C stocks (R&D) and Degradation Type (R&D) products. High priority R&D is required to advance the Degradation/Enhancement product to operational status. Medium priority R&D is required to improve the Degradation Type product.
- Biomass carbon densities – same as for Deforestation.

2 CURRENT STATE OF OPERATIONAL READINESS

2.1 *Assessing the state of operational readiness*

This section attempts to clarify the current state of operational readiness with regard to each of the GFOI forest map product specifications mentioned above. The extent to which each of the products can be generated today is assessed. The review considers the maturity of the technology, and whether the derived map products are used operationally, pre-operationally or for research by countries. Different countries have varying levels of technical expertise, and consideration of country capacity to generate the products is beyond the scope of the review. The review is concerned with the technical feasibility of each product using existing methods, sensor technologies and assuming continued access to appropriate satellite data.

In general, GFOI considers the following criteria, in order to define remote-sensing derived map products to be operational, pre-operational or R&D in this document:

<u>Operational</u>:

- Core satellite data is available for baseline mapping and time-series analysis at relevant resolution and repeatability.
- Long-term continuity of existing EO data streams.
- Data-processing methods have been documents in peer reviewed publications.
- Map production system already implemented in some countries as part of national environmental and forest monitoring programs, or demonstrated at sub-national scale.
- Processing workflows and systems are robust and repeatable.
- Methods have ideally been demonstrated to be applicable in sub/tropical forest mapping contexts.

<u>Pre-operational</u>:

- Data processing methods have been documented in peer review publications.
- Methods have ideally been demonstrated to be applicable in sub/tropical forest mapping contexts.
- Basic satellite data may not necessarily yet be available for routine baseline mapping and time-series analysis.
- Processing workflows and systems require implementation in larger-scale processing systems or national mapping programs.
- Long-term continuity and future EO data is somewhat uncertain.

<u>Research (R&D)</u>:

- Mapping methods may have been demonstrated over large areas.
- The methodology still needs to be tested as repeatable or applicable in a sub/tropical environment.
- Promising case studies exists, and help identify the extent to which additional R&D is needed to advance the methodology to operational status.

<u>Note</u>: In some cases, data availability for some data types is such that "operational" status is reached (e.g. with multi-spectral optical data), but is not yet available for other datasets (e.g. SAR). At the time of writing of this document, a number of new SAR satellite system are 6-12 months away from launch, meaning that pre-operational SAR-based mapping methods could quickly be transitioned by countries to more operational processing mode.

"Operational readiness" naturally relates to access to relevant time-series satellite data, preferably in a free and open manner, plus the level of assurance that space agencies are able to give in terms of continuity of these data streams into the next 5 – 10 years. The current and near-future availability of publicly free and open satellite data, here referred to as "GFOI core" data (including e.g., Landsat-7 and -8, Sentinel-1 and -2, CBERS-4), and commercial satellite data, here called "non-core" (e.g., RapidEye, SPOT, IRS, DMC, Worldview-2, Geoeye-1, RADARSAT-2, TerraSAR-X/TanDEM-X) data streams is considered. Reference to the GOFC-GOLD Sourcebook [54] is made in relation to data availability, product specifications (including resolution and accuracy requirements) and readiness of methods for generation of information products.

A review of the current literature, undertaken in support of product evaluation, is provided in Annex B. While the review does not claim to be exhaustive, it is believed that the examples provided present a reasonably thorough overview of available case studies worldwide. The examples demonstrate the extent to which the derived products are used operationally or pre-operationally by countries. Promising R&D case studies help identify the extent to which additional R&D is needed to advance the methodology to operational status. Each product is characterised as follows:

- National operational examples – examples where the product has been, or is routinely generated and adopted in an operational manner by a country's government (can be sub-national in scale).
  Scoring: None, Few (≤ 5), Many (>5)
- Sub-national demonstrations – examples where a product has been developed over large regions (can be national or continental in scale) in a pre-operational manner.

  Scoring: None, Few (≤ 5), Many (>5)
- Promising R&D case studies – methods have not reached pre-operational status, nor been implemented operationally by governments, but demonstrate potential for this through documented, large-area (multi-scene) R&D examples. Potential to scale-up to country level and incorporate in an operational processing stream. Methods are not yet repeatable or applicable in a sub/tropical forest context (e.g., transferability of methods for boreal-temperate forest). Can also include non-mature examples (promising, localised studies).
  Scoring: None, Few (≤ 5), Many (>5)
- EO data availability – this identifies in general terms the type of EO data used or required to generate the product by the methods or projects described in the previous three points, and whether that type of satellite data – in terms of sensor type, spatial resolution and temporal observation frequency – can be expected to be available to countries through the coordinated multi-mission satellite acquisition strategy that the Committee on Earth Observation Satellites (CEOS) has developed in support of GFOI. The *CEOS Data Strategy for GFOI* is described briefly under Section 2.2 below.
  Scoring: No, Partially, Yes

In addition, it is also noted whether there are methods/data requirements relevant to the product specification referenced in the GOFC-GOLD sourcebook [54].

The overall evaluation of operational readiness of each GFOI forest map product is presented in Table 8. Product names are colour coded according to **operational**, **pre-operational** or **R&D Phase** status.

2.2 *The CEOS Data Strategy for GFOI*

In 2011, the 25th CEOS Plenary established the Space Data Coordination Group for GFOI (SDCG; http://www.gfoi.org/coordination-satellite-data-supply), and charged it with developing a strategy to define how CEOS space agencies will coordinate their relevant Earth observing satellite systems to acquire data to support the objectives of GFOI, which includes support for national forest monitoring systems, related emissions reduction programmes and the associated national reporting requirements.

The CEOS Data Strategy for GFOI comprises a baseline, coordinated global data acquisition plan [4] that is based on a number of current and near-future “core” satellite missions from which data is/will be available free-of-charge for GFOI purposes. When fully implemented, the strategy will comprise systematic and repetitive wall-to-wall acquisitions of all forested areas globally on a sustained long-term basis. It aims to assure that any country that wishes to develop a national forest monitoring system and that wishes to participate in relevant climate frameworks, such as REDD+, can be guaranteed a minimum baseline space data coverage in support of its participation and reporting at no cost for the satellite data. GFOI will through the SDCG work with space agencies to accommodate the provision of satellite data to participating countries, at processing levels specified by the countries.

The core missions currently include:

- Landsat-7 and Landsat-8 (optical) – USGS/NASA - operational;
- Sentinel-2 series (optical) – ESA/EU - scheduled launch 2014/2015;
- CBERS-4 (optical) – INPE/CRESDA - scheduled launch 2015;
- Sentinel-1 series (C-band SAR) – ESA/EU - scheduled launch 2014/2015;
- RADARSAT Constellation Mission (C-band SAR) – CSA - scheduled launch 2018.
- CONAE and ASI are considering the possibility of including the L-band SAR SAOCOM-1 series of satellites as a core mission candidate - scheduled launch 2016/2016.
- BIOMASS (P-band SAR) – ESA Earth Explorer mission – scheduled launch 2020.

The CEOS Data Strategy for GFOI will be implemented in phases, with the observation capacity and frequency increasing as new core missions are launched and become operational:

- 2013: Of the core missions, only Landsat-7 and Landsat-8 are operational at the time of writing (October 2013). There are in average about10 observation attempts annually of every locale globally for each satellite, as part of the existing Landsat Long-Term Acquisition Plans (LTAP); [5]. The CEOS Data Strategy for GFOI recommends augmentation of the LTAP to achieve more frequent observation over GFOI participating countries, with the aim to obtain *at least* one cloud-free national coverage per year for those countries. In severe cloud covered regions however, gaps in the coverage can still be expected.

  There are no radar core missions in operation during 2013.

- 2014-2015: The CEOS Data Strategy recommends Landsat intensive coverage to include all UN-REDD and WB-FCPF participating countries. Sentinel-2A is expected to be in ramp-up operations and provide increased observation capacity over specific regions, such as Europe and Africa. Limitations can still be expected in very cloud-prone regions.

  Radar core missions: Sentinel-1A and -1B C-band SAR expected to be in ramp-up operations and with similar geographical focus as Sentinel-2.The bulk of the global land observations will be undertaken in Interferometric Wide-Swath (IWS) mode, in either single- or dual-polarisation.

- 2016+: Sentinel-2A/2B expected to be in full operations, together with Landsat-7 and -8, and CBERS-4. Weekly observations by optical sensors can be foreseen globally. Regions with remaining cloud cover problems foreseen to be very few.

  Radar core missions: Sentinel-1A and -1B C-band SAR are expected to be in full operations. SAOCOM-1 L-band SAR in operation with dual-season pan-tropical observations in dual-polarisation foreseen.

It is important to acknowledge that several commercial and Public-Private Partnership missions, referred to here as “non-core” missions, also play an important role to GFOI. This includes e.g. the optical SPOT-6/7, RapidEye and DMC (including the future DMC-3) systems, and on the radar side, TerraSAR-X/TanDEM-X, COSMO-SkyMed and ALOS-2. ALOS PALSAR, although it failed in 2011, is also relevant to mention because of the global systematic acquisition strategy that was implemented for the mission and which resulted in a consistent archive of dual-season L-band SAR data over all vegetated land areas between 2007-2011 [133].ALOS-2 comprises a similar global acquisition strategy [168]. Amongst proposed near-future non-core missions, the U.K. NovaSAR-S mission is foreseen to be launched in the 2015 time frame, and could provide SAR data at a unique new wavelength band (S-band).

These commercial and PPP missions form a part of the second component of the CEOS Data Strategy for GFOI, which supports the development of national acquisition plans and dedicated satellite data support services to countries.

The third component of the CEOS Data Strategy for GFOI concerns dedicated acquisitions and free-of-charge data provision over local scales in support of R&D activities. This activity has been on-going since 2009 within the GEO Forest Carbon Tracking Task, and comprises also non-core agencies. New satellite observations in support of the priority R&D topics identified in this document also fall within this third category of the CEOS Data Strategy for GFOI.

2.3 *Evaluation of operational status: GFOI Forest Map Products*

The following sections present a concise summary of the operational readiness assessment given in the Annex of each of the GFOI forest map product specifications (including the seven recommended products referenced in the MGD [3] and four supplementary products). Numbers in brackets in the text indicate the corresponding project or paper citations, listed in the references section. Table 7 presents an overview of the overall evaluation (colour coded by perceived operational status). Note that in this review, reference is frequently made to the GEO Forest Carbon Tracking (FCT) task, and the 11 “National Demonstrator” (ND) countries that were supported during this initial 2008-2011 phase of the establishment of the GFOI. These countries remain as “participating countries” now under the GFOI.

2.3.1 Forest/non-forest

Product specification: A map of forest/non-forest (F/NF) cover based on the national definition of forest is required. Suggested MMU < 0.5 ha and annual production frequency.

The review suggests that **Forest/non-forest** mapping can be considered **operational**, with the examples demonstrating a variety of robust methods for the generation of F/NF cover at national and sub-national scales using optical and L-band SAR data. Wall-to-wall assessments of F/NF cover at national scale in support of Approach 3 reporting can be considered operational using existing remote sensing data. Australia, India and Brazil have national operational programs for F/NF monitoring utilising GFOI core (Landsat-2) and non-core (IRS, DMC) data streams. Annual forest cover updates are produced routinely in Australia's NCAS by time-series processing of the Landsat archive [6]. India undertakes biennial forest cover mapping using time-series Landsat and IRS data and national forest inventory [30]. The Brazilian PRODES system has been in operation since 1988 and F/NF maps are generated annually over the Brazilian Legal Amazon from, primarily, Landsat, and supplemented by DMC and CBERS-2 [38]. The availability of Landsat-8 and IRS and CBERS-4 satellite series data will ensure continuity of these programs. With systematic acquisitions of C-band SAR by Sentinel-1 from 2014, and L-band SAR observations by SAOCOM in 2016 (and ALOS-2 non-core data from 2014), there is potential, where warranted, to incorporate SAR into existing programs and extend the capabilities of tropical countries where optical data is less suitable for forest cover monitoring.

There are many sub-national demonstrations and promising R&D case studies of F/NF cover mapping, and similar to LULC mapping, this is indicative of the mainstream adoption of remote sensing for broad area forest cover monitoring. Methodologies for forest cover mapping utilising core (Landsat; e.g., [31]; [32]; [33]) and non-core (IRS and MODIS, e.g., [34]; AVHRR, e.g., [35]; RapidEye and ALOS AVNIR-2, e.g., [220]; [221]; ALOS PALSAR, e.g., [31]; [17]; [18]; [220]; [221]; RADARSAT-2, e.g., [17]) data streams are fairly well advanced. As for any longer term monitoring program reliant on optical data, methods for cloud-filling using multi-scale or multi-year optical data are required. The examples indicated the need for additional R&D on the integration of alternative (e.g., high resolution data) and future satellite optical data sources (e.g., Sentinel-2) as a priority. Mapping methods, as referenced in the GOFC-GOLD Sourcebook [54], are same as for the Forest Cover Change product, and are described in the following section.

L-band dual-polarisation data (e.g., ALOS PALSAR) can be used stand-alone for wall-to-wall F/NF cover mapping. The cross-polarisation channel is critical, given its sensitivity to vegetation structure. At least one annual coverage is required for F/NF mapping, which is likely with future systematic observations by ALOS-2 and SAOCOM. In the interim, a baseline F/NF map can be generated using historic L-band data (e.g., ALOS PALSAR and JERS-1). C-band SAR is generally not sufficient on its own, and the combination of multiple frequencies and polarisations (e.g., C- and L-band dual polarisation) is recommended. Hence, the review considers F/NF cover mapping to be operational and R&D using L-band SAR and C-band SAR respectively. Only few case studies have addressed the potential benefits of the integration of multiple data sources, e.g., optical and SAR [36]; [220], and further investigation is warranted, particularly in support of tropical forest monitoring. Given the present and near-future wide availability of core and non-core SAR satellite missions, exploring the potential synergies with optical and radar is recommended to be considered a priority.

2.3.2 Forest/Non-forest change

Product specification: Maps of change in the area of forest land, including changes caused by fire or other natural factors, typically generated on an annual basis, is recommended. Suggested MMU < 0.5 ha and annual or better production frequency.

Forest/Non-forest change mapping is considered to be **operational**, with the examples found showing that medium resolution optical data is currently the primary data source for monitoring forest cover change in the tropics [37]. The extensive time-series archives of Landsat TM and ETM+ are most advantageous for forest monitoring. Critical to deriving accurate estimates of forest area change is the use of a consistent time-series of observations. Optical data can be used stand-alone if cloud-free coverage is obtained. Operational wall-to-wall forest monitoring systems exist for the Brazilian Amazon (PRODES, [38]), India (National Forest Cover Mapping, [30]), and Australia (NCAS, [6]; [39]). These programs currently rely on the availability of GFOI core (e.g., Landsat) and non-core (e.g., DMC, IRS and MODIS) data streams. Landsat TM/ETM+ data in continuous time-series or from specific epochs have been used in a few sub-national demonstrations of F/NF change mapping [18]; [40]; [104].

Recent technical issues with both Landsat-5 and -7 led to the investigation of alternate sensors (e.g., CBERS-2, SPOT, ASTER, IRS, MODIS and RapidEye) in the interim to the launch of Landsat-8 in February 2013. The examples suggest that forest monitoring strategies are well developed using these data [41]; [43]; [44]; [195], with the main limitations associated with data continuity, wall-to-wall cloud-free availability [45], and computational infrastructure [49]. Further R&D is required in these areas, and in data integration (multi-sensor and multi-scale) to improve the accuracy and reliability of F/NF change mapping using optical data sources.

Since the minimum data requirement for F/NF change mapping is one cloud-free coverage per year, the CEOS Data Strategy for GFOI can be expected to assure at least basic availability for “core” mission data for most regions of the world already from 2013, withLandsat-8 now in full operations. The observation frequency is not expected to be sufficient in very cloud-prone areas, where supplementation with commercial optical or SAR data may be required. Core data coverage will improve in certain regions in 2014-2015 with regional observations during the Sentinel-2A during ramp-up phase and to global capacity in 2016 when CBERS-4 and Sentinel-2A/2B are in full operations. Focused R&D and/or capacity-enhancement on multi-sensor cloud-free compositing and sensor interoperability will be required to fully take advantage of the large number of different sensor systems that will be available within the next few years.

The potential and complementary use of SAR for forest monitoring has been investigated in both a boreal and tropical context. L-band SAR is, due to its longer wavelength, more sensitive to forest structural parameters than C- and X-band SAR systems and can be used stand-alone [31]; [51]; [48]. Time-series data is required, with semi-annual or better coverage, and dual polarisation. An existing forest mask and dense time-series is required if C-band data are used. The extent of time-series SAR data is not as extensive as for optical systems, however decadal change monitoring has been demonstrated at sub-national scale using JERS-1 and PALSAR data [105], and there is sufficient L-band data to generate a recent baseline of forest cover against which to assess change [16]; [51]; [48]. With near-future launches and systematic data acquisition by Sentinel-1, ALOS-2 and SAOCOM, there will be further opportunities to support national forest inventory and REDD+ reporting. Hence, the review considers F/NF change mapping to be operational and R&D using L-band SAR and C-band SAR respectively.

SAR-based methods development is diverse and the potential to contribute to forest inventory has been demonstrated in several promising R&D case studies utilising both C-band (e.g., ENVISAT ASAR [42]; [46] and RADARSAT-2[47]) and L-band (e.g., PALSAR FBD and ScanSAR [48]; [50]; [161])data sources. The clear contrast and temporal consistency in forest signatures in time-series PALSAR dual-polarisation data was effective in detecting clear cuts in Sweden [48]; [161]. Multi-sensor approaches, combining L- and C-band SAR data was recommended for an operational deforestation monitoring system [46]. The combination or fusion of optical and radar data for forest monitoring has met with some success [49]. The examples suggest that further R&D would be required on methods of exploiting dense time-series X- and C-band SAR measurements (e.g., multi-temporal averaging of time-series images; [52]) to a level comparable with L-band, optimising use of time-series data for all SAR frequencies (X- to P-band), and the integration of optical and SAR data for resolving ambiguities in forest cover change information [49].

Irrespective of the data type, further improvement of temporal processing and change detection methods is needed, including the use of multi-year pixel trajectories and pixel mining techniques. Improvements in burned area mapping methods are also required, to distinguish between anthropogenic and natural processes affecting forest change.

The GOFC-GOLD Sourcebook [54] outlines the data requirements and considerations of using remote sensing data for forest area and change monitoring. The use of a Landsat-like dataset for the years 1990, 2000, 2005 and 2010, with a MMU of 1-6 ha and geo-location accuracy of less than one pixel was recommended. This review found that existing operational forest monitoring systems largely rely on Landsat or other satellite data of comparable resolution (e.g., CBERS-2 and IRS), for which appropriate time-series data are available. Additional recommendations focussed on the use of consistent methods at repeated intervals, consideration of inter-annual variability in image selection, augmenting cloudy images with coarse resolution optical data, and using high resolution data for calibration/validation. The examples in the review confirmed the availability of robust methods for forest monitoring, with priority R&D suggested for multi-scale and multi-sensor data integration, and capacity-enhancement in cloud-free compositing and temporal processing methods where requested by countries.

The Sourcebook also identified the potential use of SAR, pending data acquisition, access and methods development. The use of SAR in tropical forest monitoring has advanced considerably over the past decade, and the examples found in the review confirm its value as a complementary source of information on forest cover. Future availability of free-of-charge L-band data is uncertain, and priority R&D topics have been identified for further exploitation of time-series C-band data and its integration with optical data.

The Sourcebook also emphasised the need for higher resolution and field data for calibration/validation of forest monitoring products. The use of these data is fundamental to any remote sensing program and given due attention in the literature. Methods for relating deforestation to emissions estimation and carbon transfers between pools are also outlined in the Sourcebook. This issue is addressed in the GFOI Methods and Guidance Documentation [3].

2.3.3 Forest stratification

Product specification: A national scale map showing relevant forest types, primarily related to biomass and carbon density classes, that can be associated with specific emissions factors is required for REDD+ reporting. Primary Forest (PF), Modified Natural Forest (MNF) and Planted Forest (PlantF) may be distinguished as separate classes. Suggested MMU < 0.5 ha and 5-yearly production frequency.

Forest stratification mapping is considered to be **operational** (when stratification is limited between PF and PlantF, but pre-operational if distinguishing between several sub-strata of natural forest), with the examples highlighting the technical challenges beyond that of simply distinguishing between forest and non-forest. Forest type is not necessarily included in national operational programs, but is a requirement of REDD+ for accurate emissions reporting. The review found methods development to be diverse and include a range of segmentation, clustering, classification and modelling approaches appropriate to optical and SAR data. Advances will likely be made in further exploitation of time-series data and accounting for seasonal dynamics [135]; [131], the use of texture metrics [37], improvements in species distribution models and scaling remote sensing data (i.e., field-airborne-satellite). Assessing the consistency of methods across biomes was suggested as an R&D topic. Hence, the review considers forest stratification mapping to be operational using optical (with the caveats noted above) and pre-operational using L-band SAR data.

The CEOS Data Strategy for GFOI comprises repetitive (intra-annual) observations by both optical and SAR, aimed to enable forest stratification mapping through both time-series analysis and sensor synergy techniques. Data support capacity can be expected to be partially adequate in 2013, improving in certain regions in 2014-2015, and globally adequate from 2016.

Optical data can be used stand-alone if cloud-free coverage is obtained. At least one annual national coverage is required, although dual-season or better coverage is preferred [131]; [135]. Data from sensors that include the shortwave infra-red (SWIR) channels may improve class distinction. Copernicus Land Monitoring Services (http://land.copernicus.eu/pan-european/high-resolution-layers/forests/view) is the only example of a national operational system that includes a forest type product. The pan-European High Resolution Layers (HRL) are being produced routinely at 20 m resolution.

Methods development is progressing and there are many sub-national demonstrations of forest stratification mapping utilising both GFOI core (e.g., Landsat-7; [59]; [60]; [61]) and non-core (e.g., SPOT VGT [62]; [63], AVHRR, SPOT-5 [64], ENVISAT MERIS [63]) data sources. These data are available on a commercial (e.g., SPOT-5) or public good (e.g., AVHRR, Landsat-7) basis. One promising R&D case study employed very high resolution optical data from Quickbird to map forest types [65]. The review found that the commitment to national forest inventory (species and structural data), essential for calibration/validation of forest type classifications, is widely recognised, but not always implemented due to political or logistical issues.

Radar is not currently used for operational forest stratification mapping, however the results of numerous promising R&D case studies may warrant its inclusion in future integrated optical-radar programs. L-band SAR can be used stand-alone if dual polarisation is obtained (e.g., ALOS PALSAR [41]). Dual-season coverage and integration with optical data is preferred. C-band SAR is generally insufficient on its own (e.g., ENVISAT ASAR [211]; RADARSAT-1 [70]), and product generation using C-band SAR is considered to be still in an R&D phase. A dense time-series is typically required for discrimination of forest types [211], and ideally in combination with L-band or optical data (e.g., RADARSAT-2 and ALOS PALSAR [52]). The synergistic use of SAR and optical data has also met with some success (e.g., Landsat MSS/TM and SRTM [68]; [69], or Landsat ETM+, RADARSAT and digital video [67], or ENVISAT ASAR and IRS-P6 LISS-III [66]).

The examples suggest that priority be given to on-going methods development for data processing (e.g., filtering and texture metrics), integration (e.g., SAR-optical, SAR-SAR) and structural type classification using airborne LiDAR (*hereto after all references are made to airborne LiDAR unless specified otherwise) and InSAR [136]; [137] for improved forest stratification mapping. Simulation studies that assess the potential use of data acquired by future hyperspectral satellites for improved forest type mapping could also be considered.

The GOFC-GOLD Sourcebook [54] recommends that national carbon accounting systems base their stratification on carbon content of specific forest types. Improving forest type classifications is a suggested GFOI R&D topic.

2.3.4 All Land use categories

Product specification: A national scale map of land use categories , preferably compliant with the UN-FAO Land Cover Classification System and allowing aggregation into the six IPCC Land Cover Categories is required. Suggested MMU < 0.5 ha and annual production frequency.

The review suggests that **All Land use categories** mapping can be considered **operational**, with the examples found largely relying on time-series of optical satellite data. Annual mapping of All Land use categories at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories. Wall-to-wall assessments of land use categories mapping at national scale in support of Approach 3 (spatially explicit) reporting are operational, given at least one cloud-free national coverage per year. Multi-season imagery should be used when available, as studies have shown an improvement in mapping outcomes [15]; [126]; [55]. Technical capabilities are well advanced using satellite optical data. Country-wide land use assessments have been undertaken using entire Landsat archives (e.g., Australia's National Carbon Accounting System, NCAS [6]), or data from specific epochs (e.g., South Africa's National Land-Cover, NLC program [7]; US National Land Cover Database, NLCD [8]; Copernicus Land Monitoring Services pan-European high resolution land cover layers; and CORINE pan-European LULC mapping [9]). Alternative data sources including India's IRS satellite series, SPOT-4/5 and RapidEye data have supported national scale mapping objectives [9]. These data may not be accessible to all countries however.

The CEOS Data Strategy for GFOI can be foreseen to provide the satellite data time-series required for land use categories mapping, gradually increasing in capacity over the next few years as new core missions are launched and become operational. In 2013, when only Landsat-7 and -8 are in operations of the core missions, cloud coverage can be expected to limit sufficient availability of cloud-free data in many areas of the tropics and commercial, non-core, systems may be required to fill the gaps. In 2014 and 2015, the number of core data observations is foreseen to increase in Sentinel-2A high priority regions (refer to Section 2.2), and from 2016 and onwards, when both Sentinel-2A and -2B and CBERS-4 are in full operations, multiple cloud-free coverages can be expected to be achieved for most parts of the world.

Numerous sub-national demonstrations and promising R&D case studies using GFOI core (e.g., Landsat MSS [10]; Landsat TM/ETM+ [220]) and non-core (e.g., AVHRR [11]; MODIS [12]; SPOT-4 VGT [13]; [14]; SPOT-5, ASTER and IRS LISS-III [15]; RapidEye [220]; ALOS AVNIR-2 [221]) optical data streams are indicative of the realisation of the value, and mainstream adoption of, optical remote sensing in broad area land use monitoring. New techniques are emerging to advance the use of multi-temporal, multi-season and/or multi-sensor data [20], to produce cloud-free composites and extract information on longer-term vegetation dynamics. The impact on classification accuracy when using these temporally and/or spatially heterogeneous datasets warrants further investigation.

Alternatives such as Synthetic Aperture Radar (SAR) present an all-weather imaging capability that may be attractive to tropical countries. SAR is a useful complement to optical data, particularly in heavily cloud-affected regions [220], and provides additional information on, for example, wetlands and wetland dynamics [127] and patterns associated with biomass strata [41]; [170]. Several sub-national demonstrations confirm that dual polarisation L-band SAR can be used stand-alone for land use categories mapping (e.g., ALOS PALSAR [16]; [17]; [18]; [19]). Dual (dry and wet season) coverage can improve the discrimination of certain vegetation classes, including, for example, flooded vegetation [127]. L-band SAR data are not currently used in country-wide land use categories assessment, but with increasing availability of data and existing algorithms for processing, there is capacity to do so. Hence, the use of L-band SAR is considered pre-operational at this stage.

The availability of SAR data will increase over the next few years as new GFOI core missions are launched and become operational. In 2014 and 2015, Sentinel-1A and -1B C-band SAR will ramp-up operations in a geographical area similar to Sentinel-2. From 2016 onwards, Sentinel-1A and -1B is expected to be in full operations and dual-season pan-tropical coverage by SAOCOM L-band SAR is likely. Of the non-core missions, data from TerraSAR-X/TanDEM-X are currently available, and from mid 2014, systematic global coverages by ALOS-2 [168]. The polarimetric and interferometric capability of these sensors provides data of sufficiently high information content in support of land use categories assessment.

S-band SAR data may be available from the U.K. NovaSAR-S from the 2015 time frame. NovaSAR will be the first S-band SAR satellite mission since the Russian Almaz-1 (1991-1992) and with a wavelength between L-band and C-band (wavelength about 9.4 cm), it can be expected to provide new and complementary information about vegetation and land cover. There are however only a few studies to date on S-band SAR applications to vegetation ([217]; [218]) and the use of future S-band SAR for GFOI would consequently need to be considered in the research domain until adequately tested and validated.

Suitably calibrated data are required for extraction of information on land use categories , including corrections for terrain slope. Experienced users will implement their own corrections, however pre-processed SAR data can be purchased from space agencies or their suppliers, or supplied through GFOI (data from core missions only), with the level of processing dependent on the expertise of the user. Different countries are more advanced in their use of SAR and its integration with other satellite and ground data.

Longer wavelength SAR data (e.g., L- and P-band) is typically superior to shorter wavelength data (e.g., X- and C-band) for separation of different forest and land use categories, due largely to their increased penetration into the forest canopy [209]; [220]. Where shorter wavelength data is used (e.g., X- and C-bands), high (multiple) polarisation, dense time-series or synergistic use with lower frequency SAR or optical data is required [206]; [208]; [210]. The potential of X-band SAR for land use categories mapping has been realised in a number of promising R&D case studies (e.g., TerraSAR-X [205]; [206]; [207]; [208] and TanDEM-X [210]). A variety of methods have been applied to exploit the information content of dual and quad-polarised SAR data (e.g., decomposition, texture metrics, coherence estimation, object-based classification) to improve class separability. The reliability of these approaches needs to be tested over larger areas and in a tropical context. Hence, the use of C- and X-band SAR for land use categories mapping is considered to still be in an R&D phase.

Class separability is generally lower than for optical data, but studies have shown that the integration of L-band or C-/X-band and optical data may improve the mapping of certain land use categories. One sub-national demonstration (e.g., [159]) and numerous localised, R&D case studies (e.g., [21]; [22]; [23]; [24]; [220]) demonstrate the potential synergies between optical (e.g., Landsat TM/ETM+, ASTER, AVNIR-2) and radar (e.g., ALOS PALSAR, SIR-C) data for land use categories mapping, and reinforce the need to fully exploit the available data sources for improved mapping potential.

Further methods development in sensor interoperability (SAR-SAR and optical-SAR) and pre-processing algorithms, including open source is suggested. Ensuring access to a high resolution DEM (e.g., TanDEM-X or 30 m SRTM) for correcting SAR data would also increase usability.

The review found numerous approaches to the generation of land use products using optical and SAR data. The examples suggested that mapping would benefit from additional methods development in data integration (optical-optical, SAR-optical, SAR-SAR), use of multi-temporal and/or multi-season data and data fusion techniques. Irrespective of the type of data used, dedicated in situ calibration and validation (cal/val) measurements are essential for rigorous methodology development and transparent reporting. This was a common theme in the review, applicable to all GFOI product specifications, with further development of robust methods for the integration of satellite and ground data suggested. Global land use products are available at coarser resolution and present a useful overview of land use status. Robust means of assessing the accuracy of these global products are required.

The GOFC-GOLD Sourcebook [54] suggests that the land use categories map could form the basis for stratification to assess change in carbon stocks. Reference is given to pixel-based processing methods, including mixture models (e.g., spectral mixture analysis, SMA) and regression trees to estimate the proportion of different land cover components in optical data. It is suggested that training data is sourced from higher resolution data. The Sourcebook acknowledges existing methods for assessing the accuracy of single-date land cover maps (e.g., statistical sampling using independent reference data and measures of overall accuracy, omission and commission, or fuzzy accuracy). Aside from national inventory and emissions reporting, land use categories mapping supports a host of applications in biodiversity assessment, ecology, hydrology, agriculture and forestry, land management and conservation, and urban planning [13]; [9]; [10].

2.3.5 Land use change between forests and other land uses (Activity Data)

Product specification: A map of conversions between the six IPCC Land Cover Categories (with forest stratified as per the forest stratification product) that can be associated with specific emissions factors for REDD+ activity reporting is required. Suggested MMU < 0.5 ha and annual production frequency. Note, the Change within Forest land map (i.e., conversions between forest strata; Map number 6 in Table 6) is included in this change matrix (and not evaluated as a separate product).

Land use change mapping is considered to be **operational**, with the examples found largely relying on time-series optical data. Existing products may need modification to accord with IPCC transition categories. Annual mapping of land use change at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories. There needs to be some flexibility in the system to accommodate new transition classes, such as transitions within the Forest category (e.g., degradation, conversion to plantation), or transitions that are country-specific and deemed important for emissions monitoring.

Multi-year time-series data are required for the generation of land use change products, with multiple intra-annual observations often helpful to resolve classification ambiguities and improve classification accuracy. Australia's NCAS is one example of a national operational forest and land use change monitoring system reliant on the Landsat archive [6]. Pan-European LULCC mapping 'CORINE' is undertaken using both core (e.g., Landsat-5/7) and non-core (e.g., SPOT-4/5, IRS P6 LISS III and RapidEye) data streams. Other sub-national demonstrations have utilised both GFOI core (e.g., Landsat; [9]) and non-core (e.g., ALOS PALSAR; [17]) data streams for monitoring land use change.

The satellite data requirements for the generation of transition maps are similar to those for All Land use categories above, with the CEOS Data Strategy for GFOI expecting to provide partial solutions to the data needs in 2013, 2014 and 2015, and then in full from 2016.

Promising R&D case studies have investigated approaches to change detection [25], integration of fractional cover [26]; [27] and other multi-temporal [28] and multi-scale [29] analyses using medium (e.g., Landsat, ALOS PALSAR, SPOT-5, RADARSAT-1) and coarse (e.g., MODIS) resolution data. The case studies identify the R&D required to improve the accuracy and reliability of land use change monitoring, and so conform to IPCC land category transition mapping requirements. The review of SAR-based approaches to the generation of Activity Data found product generation to be still be in a pre-operational and R&D phase for L-band SAR and C-band SAR respectively. Continuous improvement of the satellite monitoring systems is also anticipated with future availability of high resolution DEMs and hyperspectral data. Methods for the integration of these data and incorporation in land use change classification schemes will be required.

The GOFC-GOLD Sourcebook [54] describes methods for relating land use conversions to emissions estimates and carbon transfers between pools. Monitoring post-fire land cover change and associated carbon balance is deemed important. Sources of error in large-scale land cover monitoring systems are described. Image selection is critical, with spectral data quality and geo-location accuracy paramount. The Sourcebook acknowledges the difficulty in obtaining suitable, multi-temporal reference data of higher quality for use in accuracy assessment. It also recommended that multiple dates of satellite imagery are combined to identify change directly, rather than comparing independently produced maps from different dates of imagery.

Land use change maps are useful for national inventory and also for understanding the historic driving forces of forest and land use change to inform land management and decision making [25]; [28]. Analysis of historic changes requires the availability of consistent archived satellite data, but little can be stated about the quality of the global satellite data archives. Data availability and consistency can be expected to vary significantly between sensors and geographical regions, and assessment of historical archives will therefore need to be undertaken on a country by country basis for the key sensors of interest.

2.3.6 Near-Real Time Forest Change Indicators

Product specification: A map that provides early warning indicators of potential changes in forest cover (e.g., clearing or degradation) is recommended. Coarse resolution, frequent measurement is needed to detect disturbance over large areas. Low accuracy is sufficient. The product specification is not actually required for UNFCCC or REDD+ reporting, but is useful for early warning and detection of potential and actual changes in forest cover or forest degradation. Suggested MMU > 0.5 ha and bi-monthly or better production frequency.

Near-Real Time Forest Change Indicators mapping is considered to be largely **operational**, with the review finding a few active operational monitoring programs based on optical data. INPE's DETER system is the best known example of a national operational system for Near-Real Time (NRT) forest change detection. Monthly updates are generated using MODIS data. MODIS data is widely available with routine generation of daily and composite products. These data largely fulfil the requirements of high temporal frequency and coarse spatial resolution for detecting disturbance. The examples found the coarse resolution and cloud contamination to be limiting however, and suggested that further R&D is required on cloud-filling and hyper-temporal processing methods. The use of higher resolution data (e.g., Worldview-2, Geoeye-1) for validation was also suggested.

IBAMA, Brazil, provide the only example of a pre-operational, SAR-based (PALSAR ScanSAR) system for generating deforestation information for law enforcement [57]. The wide acquisition mode of the ScanSAR provides repeat images that complement the short response time of the optical system and particularly when clouds are limiting. INPE also undertook research into the potential use of ScanSAR for detecting deforestation to prepare for future integration of Brazilian MAPSAR and CBERS-2 satellite data [58]. One promising R&D case study demonstrated hot-spot monitoring for areas at risk of deforestation using multi-temporal, high resolution SAR data (e.g., TerraSAR-X and RADARSAT-2 [199]). The review considers the use of C- and X-band SAR for early warning of forest clearing and degradation to be in an R&D phase.

Other operational early warning systems rely on MODIS data to generate a series of daily global fire-related products [54]. Further R&D is required on their integration with higher resolution data for burned area mapping and assessing fire history, vegetation type and condition, and establishing the link with carbon emissions estimation. Sub-national demonstrations and case studies are few, but an algorithm for identifying disturbance pixels from hyper-temporal Landsat data [55], and AVHRR derived green vegetation fraction images [56] are promising developments for inclusion in an early warning system. Further investigation of alternative optical (e.g., SPOT, DMC, future Sentinel-2) and SAR (e.g., future ALOS-2, Sentinel-1) data sources with high frequency coverage is suggested.

The CEOS Data Strategy for GFOI cannot be expected to provide optical core data with the high temporal frequency required for near-real time forest change monitoring in most regions of the world before the Sentinel-2 system is in full operations in 2016. The C-band SAR Sentinel-1 system will have the technical capacity to undertake frequent monitoring over forest hot-spot regions on request, and further R&D on the use of dense time-series of C-band SAR for forest change monitoring is considered a priority. Amongst non-core optical sensors, RapidEye and DMC could potentially be utilised. Frequent coverage by very high resolution satellites (e.g., RapidEye and WorldView-2) may be useful for detecting more subtle change in forest cover. On the SAR side, the ALOS-2 systematic acquisition strategy comprises, in addition to dual-season coverage in 10 m resolution mode, also wall-to-wall dual-polarisation L-band observations in ScanSAR (100 m) mode over the pan-tropical zone with 42-day repeat [168]. X-band SAR data, such as that acquired by COSMO-SkyMed and TerraSAR-X/TanDEM-X, may also prove useful. The proposed NovaSAR S-band SAR mission could provide frequent coverage for the NRT detection of forest cover change in the future, if a constellation is launched.

The GOFC-GOLD Sourcebook [54] recommends the use of coarse resolution data for identifying rapid change. Current programs reviewed by GFOI utilise MODIS data, and demonstrate potential for use of L-band ScanSAR data, but consideration should be given to future use of medium resolution sensors with high revisit capability (e.g., Sentinel series).

2.3.7 Degradation Type

Product specification: A map identifying any type of degradation or proxy thereof is recommended. At present, there is no consensus on a definition of degradation. In the context of emissions reporting, [174] proposed the following definition: “A direct human-induced long-term loss (persisting for X years or more) of at least Y % of forest carbon stocks or values since time T and not qualifying as deforestation or an elected activity under Article 3.4 of the Kyoto Protocol”. Suggested MMU > 0.5 ha and 5-yearly production frequency.

Degradation Type mapping is considered to be in the **R&D phase**, with further investigation of methods for extracting land use history from optical or other data, and exploiting potential optical-SAR synergies required for operational use. INPE’s DEGRAD system is the only existing national operational program for forest degradation monitoring. The process involves manual interpretation of Landsat and CBERS-2 imagery, and would benefit from automated methods of detecting specific types of degradation. Continuity of Landsat and CBERS series will ensure on-going access to data for methods development.

There has been limited R&D on the subject of degradation type mapping, as evidenced by the lack of sub-national demonstrations and only few case studies. Indeed, without a generally accepted definition for the term degradation, how can it be confidently detected and monitored? It is suggested that development of such a definition is a priority R&D topic.

Time-series Landsat data has demonstrated potential for extracting information on changing land use patterns (e.g., forest age, period of use) which can be associated with degradation. Optically derived vegetation fraction images can be used to classify degraded and intact forest (e.g., SPOT-4, [79]). Spectral Mixture Analysis (SMA) has been applied to multi-temporal optical data to map the extent of degraded areas and the degree of degradation. Selective logging can be identified in high to very high resolution (VHR)SAR data (e.g., TerraSAR-X, [80]; [81]; [203], and COSMO-SKyMed), and medium resolution SAR data (e.g., ALOS PALSAR, [203]). SPOT and VHR data are typically acquired on a commercial basis, and so countries would require specific investment in these technologies for methodology development. The examples suggest priority R&D in the use of fractional cover and spectral indices and advanced change detection routines using VHR data for improved degradation type mapping. One promising R&D case study demonstrated the potential use of LiDAR and field plot data for discriminating degradation and other activity-based change categories [78].

The EO data requirements for degradation type mapping can be expected to vary depending on the type of degradation (or proxy). The CEOS Data Strategy for GFOI may provide useful data for mapping/identification of the types of degradation monitored by INPE’s DEGRAD system. The availability of very high temporal resolution data from a fully operational Sentinel-2 system in 2016 can be expected to be important. Very high spatial resolution optical and SAR data have as mentioned above demonstrated capacity for mapping of selective logging and removal of individual trees. VHR data are however presently not part of the CEOS Data Strategy for GFOI and will need to be obtained through commercial data providers (or perhaps through national sponsorships if this can be arranged in future).

The GOFC-GOLD Sourcebook [54] identifies the types of degradation that could be assessed using remote sensing data, the likely spatial and temporal resolution requirements and methodologies for detection. Degradation type can be mapped directly through identification of canopy gaps and clearings, and indirectly by mapping roads and log decks. These are areas of current R&D using GFOI core and non-core data streams. While medium resolution (e.g., Landsat and SPOT) data is commonly applied to degradation mapping, the Sourcebook notes the requirement for VHR (< 5 m) and high frequency measurement (e.g., Quickbird, IKONOS, RapidEye, WorldView-2, Geoeye-1) for detecting selective logging and forest fire. The only examples of using VHR data in the review included a handful of studies using TerraSAR-X Spotlight data. Annual mapping was viewed as important to account for rapid change in spectral signatures associated with old growth and burned areas. As identified in the review, INPE's DEGRAD system monitors change on an annual basis. GOFC-GOLD methods for the detection of degradation included image enhancement, spectral unmixing and change detection. These methods form the basis of active research within GFOI in the use of optical and SAR data for forest degradation monitoring. The use of SAR for monitoring degradation was not specifically mentioned in the Sourcebook, but its complementary and potential use in tropical environments for fire-related mapping was identified in this review.

2.3.8 Degradation and/or Enhancement of Carbon Stocks

Product specification: A map showing a qualitative percent or area change in a vegetation metric from a reference condition or a quantitative estimate of biomass gain/loss in the forest class is recommended. Suggested MMU < 0.5 ha and annual production frequency.

Mapping of **Forest Degradation/Enhancement of Carbon Stocks** is considered to be in the **early R&D phase**, with further methods development required on data integration to determine the best combination of sensors for identifying and monitoring degradation over long time-scales. There is no clear definition of degradation, but it is generally accepted to include any direct, anthropogenic-induced and persistent loss in carbon density over time, but still maintaining sufficient canopy cover to meet the threshold for definition of forest and with no change in land use. The examples emphasised that the task of mapping of biomass or carbon loss/gain relative to a reference year chosen by a country is far more challenging than for deforestation [71]. Forest degradation is typically manifested through a change in forest structure, which is more difficult to detect and quantify than deforestation using remote sensing where often significant reductions in canopy cover are observed. Identification and mapping of degradation (or proxies) is a topic of key importance in climate negotiations and an area of active research. Remote sensing data might be better utilised within a sampling approach, whereby the data is initially used to stratify the forest and subsequently detect change, followed by in situ sampling and/or air photo/satellite interpretation of sampled sites.

High spatial and high temporal observations are of key importance for monitoring degraded and burnt areas [41]. There are few sub-national demonstrations of degradation monitoring utilising GFOI core (e.g., Landsat [72]; [73]) data streams. There are several promising R&D case studies however, that demonstrate qualitative estimators of degradation, e.g., defoliation mapping using MODIS [74], identification of degradation intensity using Quickbird [201], degradation monitoring using Landsat-7 ETM+ [202], and the discrimination of regrowth stage using Landsat [68], or integration of Landsat and AIRSAR data [53] or PALSAR [75]; [76] and also LiDAR data [77]. Archive data (e.g., Landsat and JERS-1) can provide insight into historic vegetation dynamics [53]. As part of the Global Forest Mapping Program [165] JERS-1 mosaics acquired between 1992-1998 [166] are available for the tropical and boreal regions, and could be further utilised. One study demonstrated the accurate detection of selective logging using TerraSAR-X Spotlight data [175], and confirmed the high reliability of detection of larger (high biomass) trees. In another study, a relationship between LiDAR-derived local maxima and TanDEM-X interferometric coherence data was observed [198], and the correlation between volume decorrelation and forest structure demonstrated potential to inform on forest stratification.

The examples suggest that priority be given to R&D and/or capacity enhancement in pixel mining and trajectory segmentation methods, SAR-optical integration, use of VHR optical (e.g., Quickbird, RapidEye) and SAR (e.g., TerraSAR-X/TanDEM-X) data, establishing reference levels using archive data, and correlating LiDAR signatures with disturbance events or even quantifying the amount of area subject to disturbances and the associated loss of carbon [78].

The EO data requirements for the generation of the Degradation and/or Enhancement of Carbon Stocks product can be expected to be similar to that for degradation type above, and vary depending on the type of degradation. The CEOS Data Strategy for GFOI can be expected to only partially satisfy the data requirements for operational generation of this product, as VHR and LIDAR data can be considered of high importance. VHR satellite data and LiDAR are available on a commercial basis.

2.3.9 Above-Ground Biomass Estimates

Product specification: A map of relevant vegetation/land cover classes stratified by above-ground biomass (AGB) that can be used to derive emissions factors for reporting is recommended. The AGB product is distinct from the degradation/enhancement of carbon stocks product in that AGB is estimated for cover classes additional to forest. Suggested MMU > 0.5 ha and 5-yearly production frequency.

The review found that **Above-ground biomass** estimation can also be considered in the **early R&D phase**, with further methods development required to estimate the uncertainty of biomass estimates and to integrate current and future data sources to reduce those uncertainties. AGB is not a deliverable product but may be used in IPCC reporting. The examples demonstrate the many technical challenges associated with the quantification and verification of biomass. National Forest Inventory (NFI) is an integral component of emissions estimation. In situ observations are required for calibration and estimation of biomass. There are concerns over the reliability of biomass inventory in relation to phenology. The reliability of ground data used to correlate with remote sensing data requires further investigation. Allometrics used in tree-level biomass estimation are not available for all species. Further development of the GlobAllomeTree tool (http://www.globallometree.org/), starting with GFOI partner countries, would be a useful endeavour. The examples highlighted the need for additional R&D on field sampling strategies and approaches to estimation and uncertainty estimation, when using field samples in combination with remote sensing measurements, as well as appropriate use of statistical estimators for biomass, especially in situations with incomplete samples due to limited field access, which is quite common in many developing countries without NFIs.

NCAS Australia is one of the few national operational examples where satellite data is used so extensively for pixel-based emissions estimation and carbon accounting [82]; [6]. Here, Landsat derived LULC and change maps are key inputs to the “FullCAM” model engine, which is used to produce forest growth and stock estimates and emissions estimates following change. On-going data collection by Landsat-8 will ensure continuity of the NCAS LULC change program.

Optical data is not physically related to biomass [179], suffers from saturation at high levels of biomass, and is therefore not suitable for stand-alone biomass estimation. Only few R&D case studies have demonstrated the use of optical data (e.g., ALOS AVNIR-2 [222]; MODIS

[41]) in estimating AGB. The review found SAR and LiDAR (both airborne and terrestrial scanners) as the more promising technologies in the pursuit of indirect retrieval of AGB, but it should also be recognised that in situ data are needed at least for model fitting/calibration (i.e., AGB on the ground modelled as a function of remote sensing variables) and ideally also for uncertainty assessment (estimation) and independent validation. SAR is useful until saturation is reached at a certain level of biomass (wavelength dependent: ~30-50 t/ha C-/X-band, 40-150 t/ha L-band, 100-300 t/ha P-band [178]; [169]). Longer wavelength data (e.g., L- or P-band) is more reliable, and several sub-national demonstrations and promising R&D studies have applied ALOS PALSAR [83]; [41]; [84]; [162], [222]; ENVISAT ASAR [85] and TerraSAR-X [170] data in model-based inversion approaches to biomass estimation. The moderate accuracies achieved are not conducive to reporting however, and the examples suggest priority R&D in investigating the capabilities of InSAR and polarimetric interferometry (POLInSAR), and assessing the transferability of methods between biomes (e.g., boreal to tropical forest). With the loss of ALOS PALSAR in 2011, polarimetric and interferometric capability has been restricted to commercially available C- and X- band SAR satellites until next generation L-band SARs become operational (core: SAOCOM-1, non-core: ALOS-2).

The examples showed forest height as one of the most important variables for biomass estimation. There are no space-borne LiDARs in operation however. A dedicated spaceborne LiDAR could revolutionize global forest inventory; however the requirements for, and specifications thereof, are beyond the scope of this review. If a more accurate forest height could be recovered from the TanDEM-X DEM, it would be possible to estimate AGB. Developing this correction is suggested as a GFOI R&D topic. Bi-static SAR presents a novel technique for estimation of global forest height [184], and is currently subject to investigation. Surrogate tree height, and hence biomass, can be retrieved from airborne LiDAR and GeoSAR data, and there is high potential to use this data to establish a baseline against which changes in carbon stocks can be monitored using future acquisitions of ALOS-2 [86]. GeoSAR data is available on a commercial basis and the cost may be prohibitive. The proposed P-band BIOMASS mission will revolutionise the global estimation of biomass, but is only due for launch in the 2020timeframe [172].It is anticipated that data collected from BIOMASS will be used to generate a global scale map of AGB at 100-200 m resolution, which can be used for initial stratification of forests and determining class-specific emissions factors. BIOMASS is considered an experimental system, and continuity of P-band data is therefore not ensured.

Airborne LiDAR data is available on a commercial basis, and several examples demonstrate its use may be more cost-effective when used in stratification approaches with satellite data [90], or when used as a sampling device where LiDAR data are collected for a sample of strips or blocks rather than wall-to-wall [91] or even as a combination of sample strips and complete coverage satellite data [92]; [180]; [194]. LiDAR-assisted biomass estimation was demonstrated for instance in Peru and Colombia [90], Nepal [Arbonaut Ltd., Pers. Comm.]; [181]; [187]; [204] and Ghana [Arbonaut Ltd., Pers. Comm.], as well as Norway [93]; [94]; [95]; [96]; [97]; [91] and Alaska [98]; [92]. LiDAR is also useful for calibration of SAR measurements [99], and can, despite high acquisition costs (particularly if repeat coverage is required), be more cost-effective to use for biomass estimation than freely available SAR data because of higher accuracy and less need for complementary in situ data which would be required for SAR to reach the same accuracy as LiDAR can provide [100]. Terrestrial Laser Scanning (TLS) is a developing technology and demonstrates high potential for rapid, cost-effective in situ measurement of forest structural parameters and calibration/validation of existing methods of biomass inventory [176]. Full-waveform measurements from overlapping scans permit 3D reconstruction of the forest for virtual direct measurement of biomass. Underlying woody debris is also observed. The review found one promising R&D study that demonstrated the potential for consistent forest metric assessment using TLS [177]. Further investigation of TLS for forest characterisation and biomass inventory is suggested.

The review found that priority R&D topics for advancing the use of LiDAR include the development of approaches to stratification, methods and statistical estimators for integration with SAR and Landsat data (with the integration with Landsat being important for calculating past emissions), optimization of ground sampling to facilitate remote sensing, estimators for sampling with LiDAR in combination with in situ observations and SAR data, and determining key influential factors (e.g., species and canopy structure) that affect the correlation with biomass.

The value of integrating multi-sensor data for biomass estimation is increasingly recognised in the review, and there are many sub-national demonstrations and promising R&D case studies on the integration of optical (e.g., Landsat, MODIS [185]) and SAR data (e.g., SRTM [87], GeoSAR and PALSAR [18]; [41], JERS-1, SRTM and QSCAT [88]), SAR (PALSAR; TerraSAR-X [173]) and LiDAR data (e.g., ICESat GLAS [41]; [89], LVIS [160]) and optical (e.g., Landsat, WorldView-2) and LiDAR data [180]; [181]. The examples highlight the need for further methods development in sensor interoperability.

The CEOS Data Strategy for GFOI does not comprise LiDAR, and until the launch of the SAOCOM-1A and -1Bconstellation in 2015/2016, also no L-band SAR core missions. Amongst non-core missions, ALOS-2 will be in operations from 2014 and airborne LiDAR is available on commercial basis.

The GOFC-GOLD Sourcebook [54] identifies the requirements for carbon stock estimation for Tier 1-3 reporting, and suggests that Tier 2 will most likely be used, but countries should aim for Tier 3. The GFOI AGB product specifications are geared towards wall-to-wall biomass assessments and Approach 3 reporting. The Sourcebook also mentions the stratification of forest types for improved carbon stock estimation. This is addressed in the GFOI forest stratification product specification, as well as in the proposed approaches to stratification and biomass estimation using LiDAR and satellite data. The inclusion of other carbon pools (e.g., below-ground and dead wood) is essential for emissions reporting. The GFOI biomass product specifications relate to above ground live biomass only; the potential to derive other carbon pools is not addressed here, and is considerably more challenging using remote sensing data. Emissions arising from biomass burning are also mentioned. Fire mapping and characterisation is not a specific GFOI product, but there is potential for data acquired by optical and SAR sensors to contribute to fire detection, burned area mapping and interrelated vegetation condition assessment.

Biomass estimates also have application in forest growth, dynamics, ecosystem process and disturbance modelling [101]; [102].

2.3.10 Change in Above-Ground Biomass

Product specification: A map showing the change in above-ground biomass (AGB) in stratified vegetation/land cover classes is recommended for emissions reporting. Suggested MMU > 0.5 ha and 5-yearly production frequency.

The review found that **Change in Above-ground Biomass** should be considered in the **early R&D phase**, with further methods development required and integration of data sources to achieve consistency in change estimates. Multi-temporal SAR and/or LiDAR, with coincident field plot data and models can be used to estimate change in AGB, but the methods for estimating AGB change using remote sensing are still very much in the research domain.

Two promising R&D examples were found that used multi-temporal ALOS PALSAR L-band data to evaluate change in forest cover in terms of biomass loss and gain in central Siberia [103] and Mozambique [171]. In Siberia, forest cover in different biomass classes was first mapped, and the change compared to an existing forest map. In Mozambique, regression and bootstrapping was used to generate maps of AGB using time-series PALSAR and field plot data. Early studies using empircal models and airborne [182] and spaceborne [183] L-band SAR measurments demonstrated the capacity for accurate tree growth monitoring. Further R&D is required to assess the potential of SAR data sources in combination with models and coincident field data for estimating change in AGB.

Few promising R&D studies were found that used multi-temporal LiDAR to estimate change in AGB at tree, plot and landscape level [78]; [163]; [164]; [165]. The strong relationships that exist between change in AGB and LIDAR-derived metrics are promising for further applications development. The review found two different approaches to estimating change in AGB, either by modelling AGB as a function of LiDAR metrics at two separate times and taking the difference, or modelling the change using combined times. Further research is needed to assess the suitability of each option for change estimation. Most studies to date have been conducted in boreal or temperate forests, and transferability of methods across biomes and forest structural types is a suggested GFOI R&D topic. Repeat, wall-to-wall national LiDAR coverage is not always a viable option for countries, but best suited to local REDD projects at sub-national scale. For large-area coverage, sampling LIDAR with coincident field plots and possibly multi-temporal optical or SAR is an active area of research.Depending on the level of management and/or forestry operations, LiDAR acquisition need not be repeated for around 10-15 years in forest that does not change much (Arbonaut Ltd., Pers. Comm). New satellite data can be integrated using LiDAR-assisted methods for estimation of AGB change.

Table 8. Evaluation of 'operational readiness' of GFOI Forest Map Products						
Product	**National operational examples**	**Sub-national demonstrations**	**Promising R&D case studies**	**EO data used in reference examples**	**Ongoing and future EO data availability by CEOS Core mission (covered by CEOS Baseline Strategy for GFOI)**	**GOFC-GOLD Methods**
Forest/non-forest[4]	**Few** Core: Australia [6] Brazil [38] Non-core: India [30]	**Many** Core: Xingu [31] Australia [32] Russia [33] Non-core: pan-European [34] Europe [35] Mexico [18] Xingu [31] Tasmania [17]	**Many** Tasmania [36] EU ReCover [220] Laos [221] Cameroon Central African Republic D.R Congo Republic of Gabon [195]	Core: Landsat-5/-7, CBERS-2 Non-core: DMC, IRS LISS, AVHRR, RapidEye, Quickbird, Kompsat-2, ALOS PALSAR, ALOS AVNIR-2, RADARSAT-2, ENVISAT ASAR	**2013-2015: Yes/Partially** **2016: Yes**	- Use Landsat-type RS data - Historical REF scenario (1990, 2000, 2005, 2010) - MMU 1-6 ha - Geo-location accuracy < 1 pixel - Consistent methods at repeated intervals - Consider inter-annual variability in image selection - Augment cloudy images with coarse resolution optical data - Potential of radar pending acquisition, access & methods - High resolution and field data for cal/val - Relating deforestation to emissions estimation, carbon transfers between pools
Forest/Non-forest change[4]	**Few** Core: Brazil [38] Australia [6], [39] India [30] Non-core: India [30]	**Few** Core: Colombia [18] Tropics & Europe [40] Australia [104] Non-core: Xingu [105]	**Many** Indonesia [45] Cameroon Central African Republic D.R Congo Republic of Gabon [195] Colombia [41] CLASlite [106] Sweden [48], [161] Indonesia [42], [50] Amazon [46] Brazil [47] Tasmania [49]	Core: Landsat-5/-7, CBERS-2 Non-core: IRS P6 LISS-II/III, RapidEye, SPOT, DMC, JERS-1, ALOS PALSAR, ENVISAT, MODIS, Terra ASTER	**2013-2015: Yes/Partially** **2016: Yes** Same as for F/NF.	
Forest stratification[5]	**Few** Europe	**Many** Core: Europe [59] Australia [60]	**Many** Guyana [41] Greece [65]	Core: Landsat-7 Non-core:	**2013-2015: Partially** **2016: Yes**	- Stratification based on carbon

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		Caribbean [61] Non-core: SE Asia [62] South America Australia [64] Congo [63]	Indonesia [52]; [211] Borneo [52] Minnesota [70] Brazil [68] Costa Rica [69] India [66] Ecuador [67]	SPOT VGT, SPOT-5, SPOT VGT, IRS, AVHRR, Quickbird, ALOS PALSAR, ENVISAT ASAR, RADARSAT, SRTM	Same as for LULC.	content of specific forest types
All Land use categories[6]	**Many** Core: South Africa [7], Australia [6] USA [8] Europe [9] Non-core: India Europe [9]	**Many** Core: Africover USA [10] Europe [9] Non-core: Asia Europe [11], [12] Wales [15] Amazon [13] Africa [14] Canada Borneo [16], [18] Tasmania [17] Central Siberia [19] Malawi[159]	**Many** Baltic [20] EU ReCover [220] Laos [221] Mexico [219] SW Brazilian Amazon [205] Uganda [206] Kalimantan [207], [210] Germany [208] Thailand [21] Bangladesh [22] Boston [23] West Africa [24]	Core: Landsat-5/-7 Non-core: IRS WiFS, IRS P6 LISS III, RapidEye, ALOS PALSAR, ALOS AVNIR-2, RADARSAT-2, ENVISAT ASAR, TerraSAR-X, TanDEM-X, SPOT-4/5, NOAA AVHRR, ASTER, MODIS, SIR-C, JERS-1, ENVISAT ASAR	**2013-2015: Partially** **2016: Yes** 2013: Landsat-7/-8. Approx 10 observation attempts globally. More frequent over GFOI priority countries, with the aim to obtain at least one cloud-free coverage per year. In severe cloud covered regions, it is unlikely to be sufficient. Non-core: Systematic coverages by e.g. RapidEye 2014-2015: Landsat intensive coverage to include all UN-REDD and WB-FCPF participating countries. Regional coverages by Sentinel-2A. Non-core: Systematic coverages by e.g. ALOS-2,	- Mixture models (e.g., spectral mixture analysis, SMA) or regression trees to estimate the proportion of different land cover components within a pixel - Training data sourced from higher resolution data - Can form basis for stratification to assess change in carbon stocks - Established methods for accuracy assessment of single-date land cover maps

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Product	**National operational examples**	**Sub-national demonstrations**	**Promising R&D case studies**	**EO data used in reference examples**	**Ongoing and future EO data availability by CEOS Core mission (covered by CEOS Baseline Strategy for GFOI)**	**GOFC-GOLD Methods**
					RapidEye 2016+: Sentinel-2A/2B in full operations, CBERS-4 in ramp-up phase. Weekly observations foreseen globally. Dual-season pan-tropical coverages by SAOCOM L-band SAR. Non-core: Systematic coverages by e.g. ALOS-2, RapidEye	
Land use change between forests and other land uses[6]	**Few** Core: Australia [6] Europe [9] Non-core: Europe [9]	**Few** Core: Non-core: Tasmania [17]	**Few** Amazon [25], [26], [27] Bolivia [28] China [29]	Core: Landsat-5/-7 Non-core: MODIS, ALOS PALSAR, SPOT-4/5, IRS P6 LISS III, RapidEye RADARSAT-1	**2013-2015: Partially** **2016: Yes** Same as for LULC.	- Relating LU conversion to emissions estimation, carbon transfers between pools - Monitoring post-fire land cover change and associated carbon balance - Image selection is critical - spectral data quality and geo-location accuracy - Difficult to source multi-temporal reference data for accuracy assessment - Preferable to combine

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Product	**National operational examples**	**Sub-national demonstrations**	**Promising R&D case studies**	**EO data used in reference examples**	**Ongoing and future EO data availability by CEOS Core mission (covered by CEOS Baseline Strategy for GFOI)**	**GOFC-GOLD Methods**
						multiple dates of satellite imagery to identify change directly, than compare independently produced maps from different dates
Near-Real Time Forest Change Indicators[7]	**Few** Core: Brazil Non-core: Brazil USA [54]	**Few** Core: USA [55] Non-core: Brazil [57], [58]	**Few** USA [56] REDD-FLAME [199]	Core: Landsat-7, CBERS-2 Non-core: MODIS, IRS, AVHRR, ALOS PALSAR ScanSAR, TerraSAR-X, RADARSAT-2, RapidEye	**2013-2015: No** **2016: Yes**	- Coarse resolution data for identifying rapid change
Degradation Type Map	**Few** Core: Brazil	**None**	**Many** Manaus Brazil Amazon [79] West Colombia [80] Panama [81] SE Norway [78] Cameroon Central African Republic D.R Congo [203]	Core: Landsat-7 Non-core: IKONOS, SPOT-4, TerraSAR-X, LiDAR, COSMO-SkyMed, ALOS PALSAR	**2013-2015: Partially** **2016: Partially**	- Direct identification of canopy gaps and clearings - Indirect mapping of roads and log decks - Very High spatial (<5 m) and temporal resolution required. - Annual detection to account for old growth forest & burned areas - Image enhancement and
Degradation and/or Enhancement of C stocks	**Few** Core: Brazil	**Few** Core: North America LandTrendr [72], [73]	**Many** Appalachian [74] Australia [53], [75], [76], [77]	Core: Landsat-7 Non-core: MODIS, ALOS PALSAR,	**2013-2015: Partially/No** **2016: Partially**	

Table 8. Evaluation of 'operational readiness' of GFOI Forest Map Products

Product	National operational examples	Sub-national demonstrations	Promising R&D case studies	EO data used in reference examples	Ongoing and future EO data availability by CEOS Core mission (covered by CEOS Baseline Strategy for GFOI)	GOFC-GOLD Methods
			Brazil [68] Gabon and D.R Congo [201] Ethiopia [202] Northern Brazil [175] Kalimantan [198]	AIRSAR, JERS-1, LiDAR, Quickbird, TerraSAR-X, TanDEM-X		spectral unmixing techniques - Change detection - SAR for fire-related monitoring
Above-Ground Biomass Estimation	**Few** Core: Australia [modelled-82], [6]	**Many** Non-core: Eastern Australia [83] NE USA [84] Boreal forest [85] Continental USA [87] Conterminus USA and Alaska [185] Colombia [18, 90] Borneo [41] Guyana [41] Mexico [41] Amazon [88] Nepal [180]	**Many** Finland PNG [86] Laos [222] Amazon [90] Maine [99] Gabon [89] Cameroon [41] D.R. Congo [41] Tanzania [41] Norway [93], [94], [95], [91], [96], [97], [158] Alaska [92], [98] Harvard forest [160] Vietnam [162] Borneo [170] Southern Finland [173] Canada [177] Nepal [181], [204], [187] Ghana [194]	Core: Landsat-7 Non-core: ALOS PALSAR, ALOS AVNIR-2, ENVISAT, TerraSAR-X, ICESat GLAS, GeoSAR, SRTM, MODIS, QSCAT, JERS-1, LIDAR, TLS, WorldView-2, RapidEye, DMC	**2013-2015: No** **2016: Partially**	- Requirements for Tiers 1-3 - Tier 2 likely most used, but aim for Tier 3 - Stratification of forest types for improved carbon stock estimation - Inclusion of other carbon pools (e.g. below-ground, dead wood) for emissions reporting - Baseline data on fire regimes & trends in emission patterns
Change in Above-Ground Biomass	**None**	**None**	**Many** Central Siberia [103] - Hirkjølen	Non-core: ALOS PALSAR LiDAR AIRSAR E-SAR	**2013-2015: No** **2016: Partially** .	

Table 8. Evaluation of 'operational readiness' of GFOI Forest Map Products						
Product	**National operational examples**	**Sub-national demonstrations**	**Promising R&D case studies**	**EO data used in reference examples**	**Ongoing and future EO data availability by CEOS Core mission (covered by CEOS Baseline Strategy for GFOI)**	**GOFC-GOLD Methods**
			experimental forest, Norway [165] - Boreal forest, Norway [78] - Northern Idaho [163] - Canada and Australia [164] - Mozambique [171] - East Anglia, UK [182], [183]	SEASAT JERS-1		

*Note: Product names are colour coded according to **operational**, **pre-operational** or **R&D Phase** status.

[4] Product considered operational for key optical datasets and L-band SAR, however still in R&D phase for C-band SAR.

[5] Product considered operational for key optical datasets when stratification is limited between primary forest (PF) and planted forest (PlantF), but pre-operational if distinguishing between several sub-strata of natural forest. Product still considered in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

[6] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively. Annual mapping of All Land use categories and change at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories.

[7] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

2.3.11 *Uncertainty and inference*

Uncertainty assessment and inference for emissions is considered to be **operational**, but only for a limited set of conditions. For the gain-loss approach, emissions for an activity are estimated as the product of an estimate of the activity area, often based on a land cover change map, and an estimate of the emissions factor for the activity. Total emissions are then estimated as the sum over activities of emissions estimates for individual activities. As per the IPCC Good Practice Guidance (GPG); [1], emissions inventories should satisfy two criteria: (i) neither over- nor under-estimation, so far as can be judged, and (ii) uncertainties are reduced as far as is practicable. The first criterion reflects the fact that maps are subject to classification errors that induce bias into the estimation procedure and cause map-based activity area estimates to deviate from their true values. Compliance with the first criterion requires estimation of this bias and compensation for it when calculating estimates of activity areas. The second criterion reflects the fact that map classification errors also induce uncertainty into any estimates obtained from maps, even if adjustments are made for bias. Reduction of that uncertainty requires that it must first be estimated using robust and statistically rigorous methods. The primary means of estimating the bias, adjusting for it, and estimating uncertainty is via comparison of observations of map units for an accuracy assessment sample and corresponding map unit classifications or class predictions.

The primary factors that affect satisfaction of the two IPCC GPG estimation criteria for estimates of activity areas are map accuracy, the accuracy assessment sampling design, and the accuracy assessment sample size. A general approach for satisfying the estimation criteria using familiar design-based approaches consists of four steps [107]:

i. For each activity, calculate an initial estimate of area based on the number of map units for which the activity has been predicted;

ii. Acquire a probability-based accuracy assessment sample of land cover change observations for two dates from sources other than the map itself;

iii. Calculate a bias adjustment term to compensate for classification errors, and adjust the initial map-based estimate from (i) accordingly;

iv. Calculate the variance of the estimate using deviations between the map predictions and observations for map units selected for the accuracy assessment sample.

Activity maps in the form of land cover change maps may be constructed using either post-classification or direct classification techniques and training data consisting of either a single set of repeated land cover observations or two independent sets of land cover observations. However, regardless of the classification technique or training data, the accuracy assessment data for a change map must consist of a set of repeated observations of the same sample locations. Further, for use with the four-step method, the accuracy assessment data must be obtained using a probability sampling design, regardless of the design used to acquire the training data. If the training data are acquired using a probability sampling design, they may also be used for accuracy assessment, although classification accuracies may be somewhat optimistic [108].

A general criterion for accuracy assessment sample data is that their quality must be as great or greater than the map class predictions [109]. Ground data that are acquired by field crews and that can be accurately co-registered to maps are generally regarded as the standard for accuracy assessment data. However, acquisition of such data for two dates at the same sample locations may be extremely challenging, particularly in tropical regions without established inventory and monitoring programs. Thus, higher resolution remotely sensed data such as aerial photography have also been used as accuracy assessment data [110]; [111].

Statistical estimators (formulae) for estimating the bias and the variance and illustrations for their use for both land cover and land cover change have begun to appear in the remote sensing literature [109]; [112]. Most of the reported studies have focused on land cover [113]; [110]; [114], although a few have assessed land cover change [115]; [116]. In addition, nearly all have relied on simple random or systematic accuracy assessment sampling designs. Generally, areas of individual land cover classes are large relative to areas of individual land cover change classes. Thus, whereas simple random or systematic accuracy assessment sampling designs may produce sufficiently large sample sizes for all land cover classes, stratified sampling designs may be necessary to obtain sufficiently large sample sizes for all land cover change classes. Stratified analyses would typically entail construction of a land cover change map and then use of the predicted change classes as strata for a stratified accuracy assessment sampling design [117]. The success of a stratified accuracy assessment sampling design depends on map accuracy as reflected by the degree to which the predicted activities correspond to the actual activities at each location. This approach would also usually require separate training and accuracy assessment samples.

In summary, general techniques for estimating activity areas from land cover change maps have been documented and reported in the literature. Thus, assessment of uncertainty and construction of inferences for activity areas may be considered operational when accuracy assessment data are available and can be acquired using a simple random or systematic sampling designs. However, an important question is whether those actively engaged in application of the gain-loss method are aware of the techniques or are comfortable using them. When stratified accuracy assessment sampling designs are required, the assessment of uncertainty and construction of inferences for activity areas must be considered pre-operational. Uncertainty assessment and inference must be considered to be in the R&D phase when probability accuracy assessment sampling designs cannot be used such as for remote and inaccessible forests or for countries with no large area sampling programs. In addition, use of the stock change method, efficient estimation of emissions factors, and the assessment of uncertainty for estimates of emissions factors must be considered to be in the R&D phase.

2.4 *Experiences from the GEO FCT R&D activities*

As noted above, GFOI has developed out of the GEO FCT programme and this section describes some of the experiences and results for key science questions from the former "GEO FCT National Demonstrator" program. This section summarises the current state and advances in methodology development, and identifies where progress has been made and where the research gaps are.

2.4.1 Optimising Information Extraction from Multi-sensor and Multi-temporal EO Data

Sensor interoperability

Sensor interoperability refers to whether the same thematic results (for the forest map products identified in Table 1) can be obtained from different sensors (to increase data acquisition opportunities or replacement in case of system failure or lack of continuity). Under the GEO FCT ND program, forest/non-forest cover, and land cover and change products generated by different optical and SAR systems were assessed for (i) full interoperability, where the same thematic results for all relevant land cover classes are achieved, or (ii) partial interoperability, with varying range of similarity for certain land cover classes. Partial interoperability is acceptable if the differences can be quantified and corrected for.

The experience of ND countries indicates the fundamental use of time-series data for all sensor types, both for change monitoring and to improve the classification accuracy. The longer the time-series, the better the accuracy becomes, due to corrections for regional and seasonal biases. In relation to SAR, the advantage of classifying over large regions is in the increased capacity to detect and correct for regional-scale backscatter variations caused by, for example, seasonality (Borneo ND), strong phenology effects or short-term meteorological disturbances (e.g., rain, drought). This was confirmed for L-band and was considered the likely scenario for C-band.

Results from F/NF and land cover mapping studies suggest full interoperability for specific scenarios utilising optical-optical systems (e.g., Brazil ND), SAR-SAR systems (e.g., Tasmania ND), and optical-SAR systems (e.g., Xingu Basin, Tasmania ND and Cameroon ND). Similar wall-to-wall estimates of total F/NF and land cover were obtained using (i) Landsat and CBERS-2 data in Brazil, (ii) ENVISAT ASAR and RADARSAT-2 data in Tasmania, and (iii) Landsat and PALSAR data in Xingu Basin, Tasmania, Cameroon and Borneo. Only partial interoperability of C- and L-band SAR for forest cover mapping was found in Tasmania. Further testing across a range of landscapes and vegetation is required, and using alternative data sources.

Optical data is the most commonly used data source by the ND countries, and is considered the most information rich. Cloud cover and the capacity to obtain targeted wall-to-wall acquisitions within short time windows were identified as the main challenges to national reporting using satellite optical data. The results of optical-optical interoperability studies are promising for continuous forest and land cover monitoring, but further R&D is needed to take advantage of data from available (e.g., Landsat-8) and future satellite sensors (e.g., Sentinel-2A/B and CBERS-4).

Studies on SAR-SAR interoperability suggest that C-band data acquired in the specific modes for ND countries are interchangeable. Future SAR-SAR interoperability (e.g.,Sentinel-1A/B, RCM) was highlighted as a desired R&D topic.

The general consensus from studies of optical-SAR interoperability was that F/NF and land cover products can similarly be generated using optical data and L-band SAR. In Xingu Basin, a similar increase in accuracy with level of class aggregation was observed using Landsat and ALOS PALSAR data: the 15-class to 2-class accuracy increased from 58 - 92.4 % (PALSAR) and 63.6 - 94.8 % (Landsat). Minor discrepancies in some class boundaries were the primary source of spatial dissimilarity between the best PALSAR and Landsat F/NF result. In Tasmania, similar total F/NF cover estimates were obtained from joint SAR-optical (PALSAR and Landsat) and all optical (Landsat-only) time-series processing. In Borneo, there was strong similarity in land cover maps generated using 50 m PALSAR and 30 m Landsat data. There was good agreement in dry land forest and dry land low biomass areas, and less agreement in wetland classes, cropland/gardens and regenerating forest/agroforestry. Timing of data acquisition and resolution were important factors, with seasonal and spatio-temporally coherent radar vs. inconsistent and incomplete Landsat coverage, and 50 m radar vs. 30 m optical resolution. Harmonisation of legends in optical and SAR data sources was recommended; however the needs of end users should be considered (i.e., class definitions in harmonised datasets should match operational needs).

Case studies using optical data and C-band SAR were few, but suggest only partial interoperability. For example, logging roads were visible for a much shorter time in RapidEye images for Borneo compared to RADARSAT-2 QP images.

Sensor complementarity

Sensor complementarity refers to obtaining additional thematic information through the synergistic use of two or more different sensors. Regarding SAR applications in forest monitoring, L-band SAR is most commonly used on account of the wavelength and global availability of PALSAR data. C-band SAR has demonstrated the capacity to provide useful additional information, in some cases even better differentiation between certain cover types (e.g., heath and peat forest) than L-band. Results from land cover mapping studies suggest the additional benefits from SAR-SAR complementarity (e.g., Borneo ND) and optical-SAR complementarity (e.g., Guyana ND).

There was increased contrast between certain land cover classes when C-band (RADARSAT-2 WB VV and HV) was used in addition to PALSAR FBD (HH and HV) in Borneo. This included pristine dry land Dipterocarp forest, acacia, rubber, oil palm (mature), heath forest (Kerangas), peat forest and primary forest. The mapping of wetlands would also benefit from the synergistic use of C- and L-band SAR. Extending the current L-band monitoring system in the future with C-band (PALSAR-2 and Sentinel-1) was recommended.

Successful demonstration of feature level fusion of multi-temporal ALOS PALSAR and Landsat data for mapping forest cover and detecting deforestation and degradation was achieved in central Guyana. Overall accuracies of 88% and 89.3% respectively were obtained.

Optimising information extraction from C-band SAR

Dual-season wall-to-wall coverage of C-band SAR was viewed as useful, but in combination with dense time-series over a few nominated verification sites. Use of the time-series was key to enhancing information extraction from C-band SAR. Results from Xingu Basin, Brazil, indicated that frequent time-series ASAR, i.e., monthly or bi-monthly, was required for reliable change detection. Dense time-series of RADARSAT-2 and ASAR data were critical for characterisation of statistical variability and seasonal variation of SAR backscatter for the main forest types in Tanzania. Good deforestation mapping results were obtained from dense time-series of ASAR APV IS4 data for Sumatra. Multi-temporal averaging of RADARSAT-2 QP images for Borneo yielded a very sharp (low speckle) image, useful for detection of logging roads arising from small-scale illegal logging. High resolution, dense time-series data, acquired at the same incidence angle and look direction were optimal for detecting these small features.

Analysis of simulated Sentinel-1A/B and RCM time-series datasets over some of the ND verification sites (using ASAR and RSAT-2 data) was a desired research task. It is suggested to be considered under GFOI priority R&D tasks.

Applications and optimal use of X-band SAR

X-band results indicate potential for forest monitoring, particularly for identification of degradation and selective logging (Colombia ND, Guyana ND). Analysis of VHR TerraSAR-X data over Guyana demonstrated the feasibility to detect narrow logging roads, and, with use of time-series data, the detection of selective logging and removal of individual trees. X-band SAR data is also highly desired for verification of derived products.

2.4.2 Biomass estimation

Several ND countries attempted to estimate Above Ground Biomass (AGB) using SAR and LiDAR data. Most countries suffered from a lack of in situ calibration and validation data, and only interim products are available. Field-based observation is on-going in some ND countries, with plot-level forest structural measurements being obtained in support of biomass inventory. Biomass stratification maps were generated using time-series (ALOS PALSAR (e.g., Cameroon ND, Mexico ND), ENVISAT ASAR (Mexico ND), and through the integration of ALOS PALSAR and ICESat GLAS height data (Kalimantan). Further R&D is required to assess the potential for quantitative estimation and stratification of biomass using these and other data sources.

2.4.3 *Data acquisition strategy*

ND activity formed the basis of a series of recommendations to CEOS and space agencies to optimise the FCT acquisition strategy for current and near-future satellite missions. The following recommendations were made, of relevance to future acquisitions for GFOI countries:

i. Continue with annual, dual season, wall-to-wall coverage over the NDs with optical, L- and C-band SAR
ii. Dense RADARSAT-2 time-series over nominated verification sites to simulate new generation C-band satellite datasets
iii. FCT community to provide guidance to ESA and CSA to ensure useful acquisitions of future C-band SAR, i.e., from Sentinel-1A/B and RCM (similar to that for ALOS and ALOS-2)
iv. VHR (optical and X-band) data highly desired for verification of maps/products generated
v. Provide access to a high resolution DEM (e.g., TanDEM-X or best available SRTM) for orthorectification and terrain illumination correction of data, and use in classification.

2.5 *Summary of main R&D needs*

Based on the above review of "operational readiness" the main R&D needs are summarised as follows (Table 9):

Table 9. Summary of research needs

R&D topic	R&D need
General forest mapping method improvements	Sensor interoperability - generating similar thematic products from different sensor systems for assembly of time-series **Relevant GFOI products:** All Land use categories, Land use change between forests and other land uses, F/NF, F/NF change, Forest stratification, Degradation, Degradation type, AGB
	Sensor complementarity for improved information extraction and monitoring, including data fusion techniques **Relevant GFOI products:** Land use categories, Land use change between forests and other land uses, F/NF, F/NF change, Forest stratification, Degradation, Degradation type, AGB
	Uncertainty and inference **Relevant GFOI products:** all
	Assess potential generation of products using simulated future datasets such as (i) Sentinel-1/RCM time-series (derived from ASAR and RSAT-2 data), (ii) Sentinel-2, and (iii) Hyperspectral (EnMAP) data **Relevant GFOI products:** Land use categories, Land use change between forests and other land uses, F/NF, F/NF change, NRT forest change, Forest stratification
	Optimising information extraction using dense time-series C-band SAR
All Land use categories mapping	Further exploitation of SAR – texture and other metrics
	Identify data needs and methods for evaluation of global product accuracy
Land use change between forests and other land uses mapping	Exploitation of SAR texture and polarimetry for greater class separability
	Sensor interoperability and complementarity for improved detection and mapping of land use change
	Use of VHR data for calibration/validation of change products

Table 9. Summary of research needs	
R&D topic	**R&D need**
F/NF mapping	Investigate alternative non-core data streams, including C-band SAR
Forest/Non-forest change mapping	Improved methods for burned area mapping
	Optimising information extraction using dense time-series SAR measurements
Near-Real Time forest change indicators mapping	Evaluation of spectral indexes to identify disturbance pixels for different forest types
	Investigate alternative non-GFOI data streams (TerraSAR-X, future ALOS-2)
	Methods and data for validation of products
	Exploiting dense time-series C-band SAR
Forest stratification	SAR texture metrics and polarimetry
	Sampling and species distribution models
	Consistent methods across biomes
	Airborne LiDAR or InSAR structural classification
	Forest type mapping from simulated future hyperspectral data
Degradation/Enhancement of C stocks	Mapping methods for regrowth
	Proxy, quantitative measures of degradation
	Deriving forest degradation products and field validation from VHR data
	Use of SAR for mapping degradation
	Use of airborne LiDAR for deriving biomass/carbon stocks and change
	Assessment of the relationship among definitions of degradation, degree of degradation that can be detected, associated accuracies, and useful kinds of remotely sensed data
Degradation Type mapping	Methods of extracting land use history (e.g., forest type and age, LULC transitions following clearing/re-clearing) from optical time-series
	Automated mapping methods
	Use of fractional cover and evaluate different spectral indices
	Change different detection approaches
Above-Ground Biomass estimation	Biomass stock stratification approaches (design- and model-based)
	Link between AGB and other carbon pools (e.g., soil carbon)
	R&D to generate more data for GlobAllomeTree tool
	Transferability of methods from boreal to temperate to tropical forest
	Airborne LiDAR and SAR tree height correction
	Bi-static SAR for estimation of forest height
	Integration of ground- and airborne LiDAR, SAR and optical data
	Integration of LiDAR and optical data (Landsat) for calculating past emissions
Change in Above-Ground Biomass	Modelling approaches using repeat LiDAR for estimating change in AGB
	Integration of repeat LiDAR and SAR data to estimate biomass change across different forest types
	Sampling design options – continuous NFI
	Transferability of methods to tropical biome
Data-Model integration	Improved ground data and soil carbon budget models for new forests areas (e.g., peat soils)
Socio-economic analysis	Drivers of change and impact on GHG emissions
	Link between EO data to enhance village livelihoods

3 SPECIFIC ADDITIONAL NEEDS IDENTIFIED BY TROPICAL COUNTRIES

GFOI is working closely with a number of countries to assess their data archives, processing capacity and immediate and longer term needs. Where country specific needs are related to data access, processing systems or capacity enhancement, these are being addressed by the specific GFOI capacity-building element, as well as UN REDD and FAO, as part of their capacity enhancements processes. Where specific R&D needs are identified, these will be included in this R&D Plan.

FAO-Forestry is providing capacity enhancement tools and training for each phase of the national forest monitoring set-up process: design and planning, data collection, data entry and management, data processing and analysis, data dissemination. Some of the phases are more standardized than others and have a general framework developed. Others are done on a country by country basis, without a specific standardized approach, since no one-method-fits-all applies to the range of countries. The following sections incorporate specific R&D priorities identified by Dr. Inge Jonckheere, FAO (Personal Comm. April, 2013).

Specific additional R&D needs were identified by several country representatives in attendance at the SilvaCarbon Workshop held in Pasadena, California, on September 6, 2013. Countries present included Colombia, Ecuador, Peru, Mexico and Guyana. Readiness of these countries for implementing REDD+, NFMS and MRV ranged from the planning phase to full implementation. Ministerial commitment to robust and transparent national forest monitoring and carbon accounting was evident. All countries acknowledged the need for a National Forest Inventory (NFI) or similar framework to supplement existing ground data with additional sample points measured following FAO guidelines. Several issues were raised concerning data supply and standardized processing, institutional frameworks and training. These are discussed below.

3.1 *Data needs and supply*

3.1.1 Data needs for continuity with forest carbon monitoring systems

All countries agreed that to fulfill national forest monitoring and REDD+ reporting needs, systematic ground measurements, either through NFI or a network of permanent sample plots, and availability of comparable satellite imagery was fundamental. GFOI could best assist countries by coordinating with EO data suppliers to improve access to low cost or free data over large areas for national forest monitoring. The level of processing would be country specific, with less experienced users wanting access to both raw and processed data.

Specific data requirements include:

i. Coarse resolution data for semi-annual early warning systems
   - SAR – best L-band (e.g., ALOS-1/-2) and/or C-/X-band (e.g., Sentinel-1) sensor data in wide beam modes;
   - Optical – MODIS or IRS LISS sensor data

ii. Medium resolution data for annual/biennial, wall-to-wall forest monitoring
   - Landsat 8 – dedicated connection to the whole catalogue, co-registered at pixel level;
   - SAR – best L-band and/or C-/X-band sensor data;

- o Other – e.g., SPOT-5, IRS LISS-III/IV, CBERS-4;

iii. High resolution data for validation – annual wall-to-wall or sample area coverage of e.g., SPOT-5/6, RapidEye, Quickbird, Ikonos, Formosat

3.1.2 Data delivery

A general issue concerning the delivery of satellite data as internet connectivity is often insufficient. Data supply by hard disk or DVD should be considered.

3.1.3 National DEM

All countries indicated the need for a national high resolution DEM for pre-processing optical and SAR imagery. Access to the TanDEM-X 5 m DEM was preferable, otherwise the SRTM or ASTER DEMs.

3.2 Specific forest map products

3.2.1 Estimates of forest degradation

This has been recognized in UNFCCC and IPCC discussions as a priority, given concerns over incentives to reduce deforestation inadvertently encouraging degradation. Most countries are in the phase of developing a wall-to-wall forest mask to have complete coverage of the forest, based on Landsat-like resolution satellite data, but the degradation information is missing. It is the technical capacity to monitor degradation that is lacking.

The following countries have specifically asked for help with forest degradation in 2013:

-Argentina: SPOT, Landsat

-Cambodia: SPOT

-Vietnam: ALOS PALSAR and optical, RapidEye interest and DMCii

-PNG: Landsat

-Democratic Republic of Congo (DRC): Landsat, Quickbird, RapidEye, ALOS PALSAR, TerraSAR-X

-Paraguay: optical data

-Ecuador: RapidEye

-Colombia: RapidEye, TerraSAR-X

-Peru: optical data

-Mexico: RapidEye

-Guyana: Landsat, TerraSAR-X

So for each of these countries and its respective (forest) ecosystems, a testing of methods, combination of optical/radar data or new algorithms would be highly desirable. Moreover the aspect of ‘monitoring’, and the option of, on a frequent basis, re-assessing the status is high priority for the countries. Viable methods for creating a preliminary degradation baseline were also flagged as priority.

3.2.2 REDD+ requirements go beyond deforestation and degradation: proxies

The other activities (e.g., conservation, sustainable management of forests and enhancement of forest carbon stocks) also have reporting requirements, which, since no land-use change is involved, may be similar to those for reporting degradation, but potentially more challenging as proxy indicators (e.g., proximity of transport infrastructure) may be less applicable. Agricultural observations may also be of interest in the context of drivers of REDD+.

For these other activities, an assessment of what remote sensing derived proxies (e.g., vegetation indices) could be used, and how they can be assessed and the likely accuracy is required.

3.2.3 All Land use categories and Activity Data

Countries are aiming to apply standardized methodologies to generate the required land use categories and Activity Data for GHG reporting. Estimating uncertainty at all stages of processing, including the results of activity data, emission factors and emission estimates, is critical. Improved methodologies for the production of All Land use categories maps and Activity Data are required.

3.2.4 Deforestation monitoring

Countries are trialing different approaches to monitoring deforestation using various combinations of ground, satellite and ancillary data to achieve Approach 3 (spatially explicit) and/or Tier 2 (country specific emission factors) reporting. Technical assistance is required in implementing improved methodologies and viable performance chains for deforestation monitoring.

3.2.5 Forest stratification

Maps of forest type/ecosystems are required by countries for national forest inventory and as a means of stratifying biomass/carbon density classes that can be associated with specific emissions factors. Countries have asked for assistance on improving methodologies for the production of ecosystem maps.

3.2.6 Fast response systems

Countries have indicated a need for fast response systems for implementing REDD+. These systems would also be useful for disaster planning and response. Guidance is required on the implementation of early warning or ‘near-real time’ systems for detection of forest clearing. Access to high frequency, coarse resolution data would be required, as mentioned previously. Further R&D is required on efficient algorithms for processing hyper-temporal data and methods for validating results.

3.3 Data processing and standardised methodologies

3.3.1 Use of radar data and limitations

For countries with dense cloud cover, there is a strong request for optimization using radar data. The potential use of radar in the Pacific area as a means of generating wall-to-wall forest map products is recognised, however the level of familiarity with radar data and processing varies. Guidance on the use and limits of radar data for forest monitoring is highly requested. A framework for processing radar data, from pre-processing to product generation is desirable.

3.3.2 General segmentation algorithms' optimization

In general, the existing basic segmentation algorithms are applied to satellite imagery. However, an optimization of the algorithm depending on the forest ecosystem would be desirable. Guidance on hierarchical (multi-resolution) segmentation, and appropriate selection and parameterisation of algorithms for specific forest types is required.

3.3.3 Sensor interoperability

Countries are requesting both optical and SAR satellite datasets for inclusion in their forest monitoring systems. Landsat-8 and Sentinel-1/-2 data are likely to be used in most countries. Data from optical and SAR sources are mostly used independently, and the capacity to integrate multi-sensor and multi-scale data for spatially explicit forest monitoring varies. Robust methodologies for the integration of optical-optical and SAR-optical sensor combinations for wall-to-wall forest assessment are required.

3.3.4 Time-series processing methods

It is recognized that wall-to-wall monitoring needs would have to be supplemented in areas of persistent cloud. Both optical and SAR data could be used for this purpose. Further R&D would be required on gap-filling methods to create continuous data layers and time-series processing methodologies relevant to optical-optical and SAR-optical datasets.

3.3.5 Cloud computing

Technical advances in computing infrastructure, in particular, cloud computing, mean that countries can now share online computational power and expertise. Cloud computing opportunities will address issues relevant to computing power, data storage and sharing, seamless integration of data and models, technology transfer, and cross-institutional collaboration, so that countries can focus on finding solutions to their monitoring needs. R&D is required on cloud computing capabilities to meet the requirements of operational EO based forest monitoring systems.

3.3.6 Burned area mapping methods

Most countries acknowledged that limited research is being done to address burned area mapping. Further R&D is required on improvements in burned area mapping methods in support of forest cover change assessment. Emissions factors associated with biomass burning are distinct from other anthropogenic activity that induces a land-use change. Methods for the integration of higher resolution data for mapping post-fire burned area extent are required.

3.4 Institutional frameworks

Many countries expressed a desire to increase capacity to develop and maintain a national REDD+ program. Long-term continuity of trained personnel, under clear inter-institutional arrangements was an important consideration. New software and training in image processing would assist in building in-country technical capacity, so the system could be operated internally. Assistance in implementing adequate spatial data infrastructure to process and store data would be required.

3.5 *National Forest Inventory*

Not all countries have an established NFI; some have a conceptual framework only, others a network of permanent sample plots implemented by research agencies/academia for other purposes. Some countries are using airborne LiDAR for validation. Assistance is required in designing an appropriate NFI or ground sampling network for carbon monitoring.

4 R&D TOPICS

This chapter identifies the precise R&D required to establish a basic national forest monitoring system and advance certain GFOI Forest Map products to operational status (high priority), improve product specifications (medium – high priority), and research novel products and other relevant issues (low priority) to support national forest monitoring systems (NFMS) and UNFCCC GHG emissions reporting. The prioritisation is based on the analysis of "operational readiness" (chapter 2), as well as the R&D needs expressed by GEO FCT and individual countries and organisations such as FAO (chapter 3).

4.1 *GHG Inventory requirements*

Estimates of GHG emissions and removals prepared according to the IPCC Guidelines should meet the requirements of the IPCC good practice. Good Practice is 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 uncertainties are reduced so far as possible. 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. This requires that inventories are transparent, complete, consistent, comparable and accurate.

While transparency, comparability and, to some extent, completeness can be achieved by applying rules or guidelines on reporting, consistency and accuracy depend on the methods used and their application.

Consistency requires that estimates are comparable over time. For example, in the case of REDD+ this will mean that current and future annual estimates will need to be compared to a reference level determined from historic estimates. This requirement for a consistent time-series of data over many years is crucial as in implementing REDD+ and determining its success countries will need to show a long-term reduction in emissions.

Accuracy is also important but pragmatically countries should consider the resources available. Accuracy is linked to completeness in the sense that, while an estimate can be made for the forest area as a whole, only by stratifying the forest area into areas with similar biomass pools and estimating each one separately can an accurate estimate be achieved. Methods are being demonstrated where a continuous distribution of biomass is determined from satellites and this used as a basis for GHG estimation. However, these methods are still at a research stage and cannot be widely used at present. The IPCC Guidelines address this by suggesting that forests be stratified into areas of similar forest types (and hence biomass concentrations). Thus to enhance accuracy the highest priority is for reliable methods are needed for forest stratification.

Another important consideration for accuracy is forest degradation and its inverse, enhancement of forest carbon. Whatever the cause, the associated changes is carbon stock are often difficult to identify remotely but can result in significant fluxes of GHG. Addressing forest degradation has also been identified by several tropical forest countries as an important development topic. So another priority issue is for methods to identify and measure forest degradation and enhancement of carbon stocks.

4.2 *Priority R&D Topics*

Two factors have been used to prioritise the R&D topics: the perceived forest country needs described in chapter 3 and the inventory considerations discussed above. It is assumed that

- it is most important to address the topics identified in Section 4.1 above: time series consistency (*note – TSC is considered a broader GFOI capacity enhancement issue and is not addressed in the R&D Plan – refer to Annex C*) and forest stratification;
- the R&D programme should concentrate on improving those products that are considered useful for a basic EO forest monitoring system, and those considered non-operational, either due to lack of regular of cost-effective data access issues, or insufficient application across different regions and forest types;
- Forest stratification is a minimum requirement and considered a higher priority than Forest/non-forest change products;
- forest degradation products are considered important as this has been identified by users as a gap in the existing data provision;
- methodology development should initially focus on using data from GFOI core missions (e.g., Landsat-8, Sentinel), both independently and interoperably.

Table 10 indicates priority R&D topics. The highest priority is to address Time Series Consistency, Satellite Sensor Interoperability and Stratification for the Land use change between forests and other land uses, Forest stratification and Degradation and/or Enhancement of C stocks products, as well as Proxy Methods for the Degradation and/or Enhancement of C stocks product.

The following sections describe a series of R&D Packages comprising specific R&D tasks related to general method improvement, specific forest map products and other issues relevant to NFMS and UNFCCC GHG emissions reporting. The R&D packages are prioritised as high, medium and low, so that initial priority is given to continuous improvement of a basic NFMS, with methods development for high and medium priority products, and lastly consideration of novel research products and socio-economic factors. The specific R&D tasks are indicative only, and subject to modification and further prioritisation by the GFOI Science Panel.

Table 10. GFOI Priority R&D topics: Approaches and issues for consideration

(yellow highlights products that are high priority,
and ✖ indicates topics that address priority issues and × are other R&D topics)

GFOI Product	Time Series Consistency	Hyper-temporal Processing	Spatio-temporal data mining	Satellite Sensor Interoperability	Stratification	Proxy Methods	Software Development & Capacity Building	Uncertainty &Inference	Data-Model Integration	Socio-economic Analysis	Overall Inventory priority	Operational Readiness
1) Forest/Non-forest	✖			✖							**Medium**	**Operational**[4]
2) Forest/Non-forest change	✖	×	×	✖			×	×	×	×	**Medium**	**Operational**[4]
3) Forest stratification				✖					×		**High**	**Operational**[5]
4) All Land use categories	✖			✖							**Medium**	**Operational**[6]
5) Land use change between forests and other land uses	✖	×	×	✖	✖		×	×	×	×	**High**	**Operational**[6]
6) Change within Forest land	✖	×	×	✖	✖			×	×		**High**	**Operational**[5]
7) Near-Real Time Forest Change Indicators	✖	×	×					×		×	**Medium**	**Operational**[7]
8) Degradation type map	✖	×	×	✖		✖					**Medium**	**R&D Topic**
9) Degradation and/or Enhancement of C stocks	✖	×	×	✖	✖	✖	×	×	×	×	**High**	**R&D Topic**
10) Above-ground Biomass Estimates				✖	✖			×	×		**Low**	**R&D Topic**
11) Change in Above-ground Biomass				✖	✖			×	×		**Low**	**R&D Topic**
Tropic Forest Country request	✖	×		✖		✖	×	×				

[4] Product considered operational for key optical datasets and L-band SAR, however still in R&D phase for C-band SAR.

[5] Product considered operational for key optical datasets when stratification is limited between primary forest (PF) and planted forest (PlantF), but pre-operational if distinguishing between several sub-strata of natural forest. Product still considered in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

[6] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively. Annual mapping of All Land use categories and change at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories.

[7] Product considered operational for key optical datasets, however still in pre-operational and R&D phase for L-band SAR and C-band SAR respectively.

4.3 *High priority R&D*

High priority R&D is required to support the continuous improvement of basic national forest monitoring systems for UNFCCC GHG emissions reporting. Three major R&D packages are proposed: (P1) General method improvement, (P2) Improvements to GFOI Forest Map Product specifications, and (P3) Data-Model integration. P1 addresses general method improvement (i.e., sensor interoperability and complementarity, uncertainty and inference) to increase the reliability of satellite derived forest map products for use in estimating emissions. Initial high priority is given to general method improvement relating to the Land use change between forests and other land uses, Forest stratification and Degradation and/or Enhancement of C stocks products. P2 identifies specific R&D to improve or advance high priority forest map products to operational status for inclusion in NFMS. P3 addresses the use and applicability of spatially explicit (Approach 3) GHG budget models for emissions reporting in differing national circumstances.

R&D Package 1 (P1): General method improvement

(i) Satellite sensor interoperability and complementarity

NFMS Issue

Complete carbon stock changes and emissions and removals of greenhouse gases need to be measured consistently over time and in a comparable way both nationally and internationally. The use of different satellite sensors is required as some areas with heavy cloud cover may be impossible to routinely monitor, and over time, different satellites with different sensors will be available. The consistency, comparability and methods of combining these different satellite sensors (i.e., interoperability) needs to be demonstrated, together with the uncertainties involved, in order for robust, comparable national time-series for GHG emissions to be derived.

Remote Sensing Considerations

The importance of wall-to-wall long time-series satellite data that go back to baselines chosen by individual countries is paramount in tracking deforestation, reforestation or afforestation activities and estimation of associated GHG emissions. This is required by the UNFCCC as recommended in the IPCC “Good Practice Guidelines”. Sub-hectare resolution transitions are the preferred levels of detail for spatially explicit, Approach 3 reporting. Therefore annual time-series of mid-resolution (sub-50 m pixel) satellite data is the preferred resolution for detailed mapping of forest change areas and transitions that would satisfy such requirements as countries move from Approach 1 and 2 to Approach 3 MRV approaches.

The combination of multi-scale optical data sources has proven useful for cloud-free compositing and gap filling for continuous forest monitoring. Further R&D is required on the achievable accuracy in time-series forest change mapping when combining medium (e.g., Landsat, CBERS-2) and coarse resolution (e.g., MODIS, AVHRR) and/or very high resolution (e.g., RapidEye) optical data sources, taking into account seasonal differences, climatic/environmental factors, and geometric inconsistencies.

The complementary nature of optical and synthetic aperture radar (SAR) imaging systems, in particular over heavily clouded areas, provides the opportunity for interlacing forest cover maps derived from both sensor technologies into seamless time-series forest cover maps.

R&D Topics

It is suggested that further R&D is required to optimise information extraction from optical and SAR satellite data and so improve the accuracy of forest information products. Specifically, an assessment of the following:

i. Assessment of key EO sensors regarding the achievable accuracy of time-series of annual forest/land use/change area mapping, when using only core optical satellite sensors in the time-series (e.g. Landsat; Sentinel-2), versus replacing some of the Landsat scenes or individual pixels from data derived with alternative optical sensors (e.g. CBERS-4, RapidEye, AWIFS).

ii. Assessment of achievable accuracies in time-series of annual forest/land use/change mapping, when interspersing core optical data-derived thematic products/scenes, with C- or L-band SAR-derived products/scenes.

iii. Assessment of achievable accuracies in time-series of annual forest/land use/change mapping, when interspersing L-band SAR derived thematic products/scenes, with C- or X-band SAR-derived products/scenes.

Other suggested R&D topics that address sensor interoperability and complementarity include:

iv. Data fusion techniques for the integration of optical and SAR data.

v. Cost-benefit assessment of different combinations of satellite data, ground data and LiDAR/InSAR - to determine the optimal combination of different data sources in terms of costs and accuracy (i.e., benefits).

vi. Assess potential generation of products using simulated (i) Sentinel-1/RCM time-series (derived from ENVISAT ASAR and RADARSAT-2 data), (ii) Sentinel-2/CBERS-4 (derived from Landsat data), and (iii) Hyperspectral (EnMAP) data.

(ii) Uncertainty and inference

NFMS Issue

The IPCC Good Practice Guidance establishes two criteria for tropical inventories focused on carbon accounting. The first criterion is stated in terms of avoiding both under- and over-estimates and the second criterion is stated in terms of reducing uncertainties. For remote sensing applications, this means that the effects of classification error must be both estimated and minimized. Of importance, it is the effects of classification error on remote sensing-based forest area and area change estimates that must be estimated, not the classification errors themselves (although these errors must also be estimated). Methods for extending map accuracy indices and confusion matrices to confidence intervals are increasingly available, but only for a few common classification techniques and for a small number of accuracy assessment sampling designs [116]; [118]. These methods require extension and articulation for a greater variety of classification and prediction techniques and for accuracy assessment sampling designs optimized for satisfaction of the IPCC Good Practice Guidance estimation criteria.

GFOI share the concerns of experts in this field, and information on these topics is being considered for inclusion in the GFOI Methods and Guidance Document, and likewise in the GOFC-GOLD Sourcebook.

Remote Sensing Considerations

Two categories of classification techniques are commonly used, post-classification and direct classification. With post-classification, two land cover classifications are constructed separately using two sets of land cover training data and two sets of remotely sensed data;

land cover change is assessed by comparing the two land cover classifications [115]; [116]; [119]. With direct classification, a single classification of change is constructed using a single set of forest change training data and data for two sets of remotely sensed data. Within the remote sensing community, direct classification is usually preferred to post-classification. However, direct classification is often not possible such as when change is estimated from an historical baseline map, when repeated observations of the same sample units are not possible, and when sufficient observations of change are not available for training a classifier. In addition, comparisons of change estimates obtained using post- and direct classifications for the same datasets are not known to have been reported.

The familiar and most frequently used approaches to accuracy assessment and inference are characterized as design-based because they rely on probability accuracy assessment sampling designs for validity. With design-based inference, assessment of the accuracy of a change map and construction of confidence intervals for areas of change by class require sufficient accuracy assessment observations of change for each class. Accuracy assessment datasets acquired using simple random and systematic accuracy sampling designs often do not satisfy the sufficiency requirement, particularly for rare change classes. For these cases, stratified accuracy assessment sampling designs with strata defined by change classes are necessary. Stratified accuracy assessment sampling entails multiple challenges: (i) construction of change classification is first required to identify strata, (ii) the training dataset usually cannot also be used as an accuracy assessment dataset because it was unlikely to have been acquired using the appropriate stratified design, and (iii) the efficiencies of stratified sampling designs are directly related to the accuracies of the change classifications which are usually less than the accuracies of land cover classifications.

For tropical countries, particularly those without well-established national forest inventories (NFI) or monitoring, reporting, and verification programs (MRV), acquisition of accuracy assessment data with probability sampling designs as required for design-based inference may be difficult, if not impossible. For these cases, the less familiar model-based approach to inference is a viable alternative [120]; [113]; [119]; [93]. With model-based inference, the basis for the validity of inference is the correctness of the model characterizing the relationship between the forest attribute of interest and the remotely sensed data. Thus, if a model of the relationship between sample observations of the forest attribute and the remotely sensed data can be constructed, regardless of how the sample was acquired, then model-based inference may be considered. Of importance, model-based inference may be used with both probability and non-probability accuracy assessment sampling designs, and in that sense it is much more flexible than design-based inference. The advantages of model-based inference are that probability samples are not necessary, valid confidence intervals are possible for small areas for which sample sizes are insufficient for design-based inference, and uncertainty may be estimated for each map unit, not just those in the sample as for design-based inference. The disadvantages are that familiar accuracy indices may not be possible to estimate, models must be correctly specified, and computational intensity may be considerably greater.

The precision of estimates obtained using the gain-loss method depends on the precision of both the estimates of activity areas and emissions factors. Little if any attention has been devoted to methods for accurately and precisely estimating emissions factors. Although NFI data are an important potential source of information for this purpose, sparse NFI sampling intensities may inhibit realization of the potential. The emerging capability of LiDAR, in combination with NFI data, merits serious consideration as a means of realizing this potential. However, empirical evidence of the utility of LiDAR data for estimating change is still limited [78].

With the stock change method, emissions are estimated as mean annual differences in carbon stocks between two points in time. The stock change method is mostly associated with sample-based inventories such as NFIs with more than one cycle of data [121]. As tropical countries increasingly develop NFIs in support of or in parallel with MRVs (e.g., Brazil, Guyana, Mexico, Peru, Tanzania), the relevance of the stock change method increases. If an NFI sampling intensity is sufficiently great, particularly when using large proportions of permanent plots, biomass and carbon change by land-use change class can be accurately and precisely estimated. An advantage of long-established NFIs is that they are well-documented with respect to the validity and completeness of the data, assumptions, and models. In addition, their use of unbiased statistical estimators yields estimates that contribute to satisfying the IPCC GPG estimation criteria for neither over- nor under-estimation and reduction of uncertainties [1]. Although new tropical NFIs do not have such long histories, their methods and documentation inevitably build on the historical NFI lessons learned with respect to sampling designs, field protocols, and statistical estimators. For NFIs with only a single cycle of measurements, Maniatis and Mollicone [122] describe how crude change estimates may be calculated.

Because NFI sampling intensities rarely exceed 1 plot/km^2, even in boreal and temperate forests [123], stock change methods may be perceived as inhibiting satisfaction of the spatial explicitness requirements associated with Approach 3. In addition, these sparse sampling NFI intensities may mean that not all change categories or activities will be sampled or that sample sizes will be insufficient to produce acceptably precise estimates. However, remotely sensed data has already been demonstrated to be a source of auxiliary information that can be used to partially address both these disadvantages [96]; [94]; [120]; [113]; [119]; [78].

Activities to operationalise the academic work

In the field of uncertainty and accuracy metrics, it is suggested that GFOI undertake priority R&D in the following areas:

i. Methods for deriving confidence intervals from thematic products.

ii. Methods for the transition from thematic products to various kinds of emissions estimates that address IPCC GHG criteria.

iii. Comparing uncertainties in tropical versus temperate forest biomass estimation (with same forest measurement techniques)

iv. Greater development of post-classification techniques and rigorous comparisons of post- and direct classification techniques.

v. Additional research on methods in support of stratified accuracy assessment sampling designs as a means of increasing the precision of estimates of activity areas.

vi. Additional research on the utility of model-based inference for use with the gain-loss method.

vii. Robust methods for in situ data collection and augmenting existing NFI where warranted for calibration/validation of Forest Map Products. Identification of type of cal/val data to support product generation and validation.

viii. Additional research on assessing the utility of augmenting field observations with auxiliary LiDAR data or even remote piloted/unmanned aerial systems (RPAS/UAS) for estimating change, including estimation of emission factors, and their uncertainties.

ix. Additional research on the use of the stock change method:

- Illustrations of the utility of the stock change method.
- Use of remotely sensed data to enhance stock change estimates.

R&D Package 2 (P2): Improvements to GFOI Forest Map Product specifications

(i) Land use change between forests and other land uses (Activity Data)

NFMS Issue

To calculate net carbon emissions, countries may want to produce activity data on land use change. Alternatively, by following the stock-change approach, it is feasible to produce a net carbon change estimate without knowledge of the activity. For Approach 3 reporting, spatially explicit mapping of the transitions between the six IPCC land cover categories (forest, grassland, cropland, wetlands, settlements and other land) is required. Emissions calculations are dependent on the transition type and so accurate determination of country specific transition classes and change thereof is required.

Remote Sensing Considerations

Time-series data are a requirement for monitoring changes in forest and land use categories. The changes are then attributed with an activity (e.g., FC: Forest to Cropland as a result of clearing and subsequent planting). Training data is required for attribution and is gained through local knowledge and/or using the contextual information in remote sensing data. Of particular concern, training data must include sufficient numbers of observations for each activity to facilitate accurate and precise estimation of the areas of those activities.

Forest and land use change is typically assessed at the pixel level. Robust geometric and radiometric correction of data is fundamental to ensuring pixel-to-pixel co-registration accuracy and consistent reflectance values for change assessment. More effective use of time-series data would avoid biases caused by seasonal and other variations. Forest and land use change may be better assessed by first defining the minimum mapping unit (e.g., around 3-4 times larger than the pixel size) for training and validation. Single pixels are very difficult to locate on the ground and even in VHR imagery. Statistically valid sample distributions need take into account the natural variations within a validation site.

The integration of optical and SAR data can improve the mapping of forest and land use change. If greater class separability can be achieved, then the results of change detection will be more accurate.

Activity data should incorporate country specific land use categories where appropriate. The transitions between these and standard IPCC categories may be important to country wide MRV and emissions reporting. Including these additional categories will increase the complexity of the transition matrix, but provide a more detailed picture of land use change in the region.

R&D Topics

The review found that land use change mapping was considered to be operational , with further R&D needed to develop a better understanding of the emissions associated with specific land use transitions, including:

i. Development of methods for more efficient use of time-series data, e.g., resolving ambiguities in change classes, and attribution of activity using sparse training data and contextual information.

ii. Improved mapping potential through optical-optical, optical-radar and radar-radar interoperability (refer to P1: Satellite sensor interoperability and complementarity). Key tasks include:

   - Assessment of key EO sensors regarding the achievable accuracy of time-series of annual land use change area mapping, when using only core optical satellite sensors in the time-series (e.g. Landsat; Sentinel-2), versus replacing some of the Landsat scenes or individual pixels from data derived with alternative optical sensors (e.g. CBERS-4, RapidEye, AWIFS).

- Assessment of achievable accuracies in time-series of annual land use change area mapping, when interspersing core optical data-derived thematic products/scenes, with C- or L-band SAR-derived products/scenes.
- Assessment of achievable accuracies in time-series of annual land use change area mapping, when interspersing L-band SAR derived thematic products/scenes, with C- or X-band SAR-derived products/scenes.

iii. Further development of methods that exploit the texture and polarimetry of radar and unique reflectance signatures in optical data for greater class separability.

iv. Methods for future integration of high resolution DEMs and other satellite data as they become available (refer to P1: Satellite sensor interoperability and complementarity).

v. Identify in situ and VHR data needs and methods for calibration/validation of change products.

(ii) Forest stratification

NFMS Issue

To accurately measure Greenhouse Gas (GHG) emissions and removals, countries need to stratify their forests according to type and carbon stocks. For many countries without a tradition of ground-based National Forest Inventories, the extent of different forest types is poorly known at the scale needed for accurate national forest monitoring systems and remote sensing can provide this information.

Remote Sensing Considerations

To estimate emissions associated with transitions between land categories (e.g., from forest to grassland), more detailed information is needed on what type of forests are present (e.g., peat swamp forest, mangrove, low density forests with canopy levels <20 %, primary vs. secondary forest, soft or hardwood plantations). The type of forest will influence the starting carbon pools and subsequent carbon loss during transitions.

The differentiation of different forest types is more technically challenging than simple presence/absence of forest. Optical data is considered more information rich than SAR data for mapping of forest types. At a very minimum, one annual, cloud-free national coverage is required. A multi-seasonal time-series will better account for seasonal dynamics and plantation cycles.

Classification accuracy tends to decrease with an increasing number of classes. The integration of optical and SAR or other data may improve the accuracy of discrimination of forest types. SAR provides an added dimension, given the sensitivity to biomass and canopy volume. SAR texture metrics and polarimetry can be better exploited to discriminate forest type/stratification. Segmentation algorithms, applied to optical and SAR data to create statistically homogeneous clusters suitable for classification, could be optimised depending on the forest ecosystem. The feasibility of LiDAR and InSAR for classification of forest structural types also warrants further investigation.

Sparse training data can be problematic for classifying forest stratification. National Forest Inventory may be sporadic and concentrated in accessible areas, with under-sampling of minor or remote forest communities. High to VHR resolution satellite data and local (expert) knowledge is useful for interpreting and collecting sufficient training and validation data. Further R&D is required on alternative approaches to classification, including vegetation community and species distribution models, and the integration of ground and satellite data for calibration of algorithms and validation of results. An assessment of the consistency of methods across biomes would help determine the data needs and robustness of methods for forest type classification.

Future collection of hyperspectral satellite data will likely benefit the discrimination of forest stratification. The higher spectral resolution and inclusion of the shortwave infrared (SWIR) channels may extend the range of spectrally-distinct species/types. Methods development could focus on simulating future hyperspectral datasets using airborne data if available, and application of advanced spectral processing routines for improved forest stratification mapping.

R&D Topics

The review found that Forest stratification mapping was considered to be operational when stratification was limited between primary forest and planted forest (but pre-operational if distinguishing between several sub-strata of natural forest), and would benefit from additional R&D in the following areas:

i. Further exploitation of optical-radar and radar-radar synergy for improved discrimination of forest types.

ii. Use of SAR texture metrics and polarimetry.

iii. Optimisation of segmentation algorithms for different forest ecosystems.

iv. Classification of forest structural types using LiDAR or InSAR data.

v. Improvements to species distribution modelling and scaling/integrating remote sensing data.

vi. Assessment of the consistency of methods across biomes to determine the data needs and robustness of methods.

vii. Assessment of the potential use of future hyperspectral satellite data.

(iii) Degradation and/or Enhancement of C Stocks

NFMS Issue

Monitoring forests for greenhouse gas emissions and removals (for example, as needed for REDD+) requires not just monitoring changes in forest area (needed for deforestation emissions) but also changes in carbon stocks in standing forests. While this is an area of current research interest, currently there are no EO approaches to measure directly changes in biomass or carbon stocks that are widely and routinely applicable. An understanding of what can be recommended as an operational approach to fill this gap is needed.

Remote Sensing Considerations

While the areas of some forest parcels do not appear to change from year to year, some natural and man-made impacts may cause the forest to ‘degrade’ resulting in a progressive loss of biomass/carbon per unit area. Conversely in areas left to regenerate, a gradual increase in biomass/carbon per unit area is observed. Thus, robust remote sensing methodologies are required that can provide quantitative measures of the change in carbon stocks in forest areas remaining forest. Consistent time-series observations are critical. Stable reference sites (e.g., 5 – 10 years prior in undisturbed forest) against which to quantify change can be used to identify thresholds for what is a degraded or natural forest/natural state. Identifying and quantifying the change in biomass/carbon as compared to a reference level could assist in targeted restoration to achieve natural state. A consistent approach to identifying reference levels, against which to quantify degradation is required.

Many remote sensing-derived products are indirect measures or surrogates of forest cover change and are not directly sensitive to changes in biomass. Qualitative change from a reference condition can be estimated using proxies, for example, length of logging roads can be assumed to cause a percent loss in carbon with a distance from the road (measured by ground data). Proxy methods need to be demonstrated for widespread use.

Research is needed to define what sensors and technologies are most suitable for each different type of degradation. Different degradation types such as selective logging, fires, drought, pests or new logging roads, will probably require a different technology as compared to mild fire impacts, or gradual forest loss due to pests. High to VHR data is required for mapping degradation which involves the removal of individual trees. Remote sensing observations may not always present the best solution and those cases where field sampling is more appropriate need to be identified. Accuracy metrics and uncertainties associated with estimation of carbon stock changes also need to be known. Alternative sensors such as full-waveform LiDAR demonstrate potential for forest disturbance monitoring, but even conventional discrete return LiDARs appear to be sensitive to disturbances, even in sub-canopy layers. Further R&D is required to advance the methods for operational use.

R&D Topics

The review found that Forest Degradation/Enhancement of C stocks mapping was considered to be in the R&D phase. The following topics are suggested for R&D to advance the capabilities for degradation monitoring:

i. Determine the optimal methods for mapping regrowth.

ii. Identification of the proxies that can be monitored, the ground measurements needed to calibrate the methods, and development of recommendations for routine use.

iii. Assessment of sensor interoperability and complementarity for each different type of degradation (refer to P1: Satellite sensor interoperability and complementarity).

iv. Potential use of VHR optical and SAR data for degradation mapping involving the removal of individual trees.

v. Identification of the limits of remote sensing for forest degradation monitoring, including accuracy metrics for estimation of carbon stocks (refer to P1: Uncertainty and inference).

vi. Use of discrete and full-waveform LiDAR for deriving biomass/carbon stocks and change.

R&D Package 3 (P3): Data-Model Integration

NFMS Issue

The IPCC GPG offers a range of different approaches for estimation of emissions associated with land-use transitions, including the use of spatially-explicit GHG-budget models. However, there is little guidance on the use and applicability of the most detailed Approach 3 methods, and how these relate to the available remote sensing data. A range of different approaches are used and there needs to be some advice on their applicability in differing national circumstances.

Therefore GFOI wishes to support R&D that further improves the input data and model integration, to achieve more stable and repeatable annual emissions estimates.

Remote Sensing Considerations

There are a range of Approach 3 methods currently being used. There are forest inventory-based approaches (e.g., US, Finland), or mixed inventory and remote sensing approaches (e.g., Canada), versus fully spatially explicit remote sensing, ground data and forest carbon process-model approaches (e.g., Australia, India and Brazil). However, it is not clear which approach is best suited to any particular national circumstances, nor how the approach relates to the choice and use of remote sensing data. Cost-efficient methods for reporting following the IPCC Guidelines can be quite different to forest monitoring for economic harvesting of timber.

R&D Topics

It is suggested that priority R&D be undertaken in the following areas to assess the benefits of different approaches to estimation of emissions:

i. Comparison of uncertainty/accuracy of greenhouse gas emissions and error propagation from different data-model integration approaches, e.g., comparison of forest inventory-based approaches, mixed inventory and remote sensing approaches, and fully spatially explicit remote sensing, ground data and forest carbon process-model approaches.

ii. Assessment of soil carbon budget dynamics in peat forests, versus lowland or upland tropical forests. Carbon budget models in special cases such as peat land and different types of tropical forests are still required, since there is limited field information and process modelling for such areas where the size of the different carbon pools, soil respiration and carbon loss upon deforestation are still lacking for different forest types.

4.4 *Medium Priority R&D*

Medium priority R&D is required to improve methodologies for the production of forest map products. One R&D package is proposed: (P4) Improvements to GFOI Forest Map Product Specifications. WP4 identifies specific R&D to improve or advance forest map products, including All Land use categories, F/NF, Forest/non-forest Change, NRT Forest Change Indicators and Degradation Type to operational status for inclusion in NFMS.

R&D Package 4 (P4): Improvements to GFOI Forest Map Product Specifications

(i) All Land use categories

NFMS Issue

Approach 3 reporting requires spatially explicit information on national land use. Classification schemes should be compliant with the UN-FAO Land Cover Classification System (LCCS) or allow aggregation into the six IPCC land categories (forest land, grassland, cropland, wetlands, settlements and other land). Land use data is required for emissions reporting, and further subdivision of the forest land category will likely be necessary (e.g., natural forest and plantation).

Remote Sensing Considerations

Medium resolution (30 m) Landsat-like data, acquired on an annual basis, is required for land use mapping. Continuous, cloud-free coverage is often difficult to obtain in the tropics, and compositing using previous years' imagery and other coarser resolution imagery is typically applied. Multi-temporal processing should take into account the seasonal dynamics of land cover [15]; [126]; [55].

Given suitably calibrated SAR data, complementary information on land use can be obtained [17]; [18]. Ambiguities in certain classes may be resolved through the integrated use of optical and SAR data [16]; [159] and multi-frequency SAR data [21]; [22]; [23], hence studies on interoperability/complementarity are important for continuous improvement of land use monitoring systems.

The scale of land use mapping affects the distribution and accuracy of cover classes. Different approaches to validation of coarse resolution global land use maps (vs. regional/national scale maps) are needed.

R&D Topics

Although the review found land use categories mapping to be considered operational, further improvements are possible through R&D in the following areas:

i. Improved mapping potential through optical-optical, optical-radar and radar-radar interoperability (refer to P1: Satellite sensor interoperability and complementarity). Key tasks include:

    - Assessment of key EO sensors regarding the achievable accuracy of time-series of annual land use mapping, when using only <u>core optical</u> satellite sensors in the time-series (e.g. Landsat; Sentinel-2), versus replacing some of the Landsat scenes or individual pixels from data derived with <u>alternative optical</u> sensors (e.g. CBERS-4, RapidEye, AWIFS).
    - Assessment of achievable accuracies in time-series of annual land use mapping, when interspersing <u>core optical</u> data-derived thematic products/scenes, with <u>C- or L-band SAR</u>-derived products/scenes.
    - Assessment of achievable accuracies in time-series of annual land use mapping, when interspersing <u>L-band SAR</u> derived thematic products/scenes, with <u>C- or X-band SAR</u>-derived products/scenes.

ii. Further exploitation of SAR data through extraction of texture and other derived metrics.

iii. Robust methods for integration of satellite and ground data.

iv. Identify data and methods for validating global land use categories maps.

(ii) Forest/Non-forest

NFMS Issue

The national definition of forest is used as the basis for producing a map of forest/non-forest (F/NF) cover. F/NF data is required for REDD+ reporting.

Remote Sensing Considerations

F/NF maps can be produced independently or derived by aggregating the All Land use categories product, if available. Irrespectively, a continuous time-series of observations is required for robust and accurate mapping of F/NF cover. The optimal forest monitoring system incorporates mapping methods that are robust and repeatable, and applied within a system that is adaptable to new data as collected, including that acquired by next generation sensors.

Forest definitions vary between countries, with quantitative thresholds for minimum forest area, tree crown cover, and minimum tree height. Tree height is not easily estimated and its practical use in defining the forest area is doubtful. The achievable forest/non-forest mapping accuracies using remote sensing data and according to national forest definitions should be assessed.

Continuous improvement of F/NF mapping is possible with the use of multi-scale and multi-sensor data. High resolution data is available for forest cover mapping at tree-stand scale, if required for national MRV or other purposes (e.g., tree clearing/compliance monitoring, biodiversity assessment). There are greater opportunities for discrimination of F/NF classes through the integration of optical and SAR data. Further exploitation of optical- (e.g., foliar chemistry and leaf/canopy moisture content) and SAR-derived (e.g., canopy density and structure, biomass strata) components is required.

R&D Topics

Although the review found that F/NF mapping was considered operational, existing and future monitoring programs could benefit from additional R&D on the following:

i. Integration of alternative (high resolution) data for fine-scale inventory where required.

ii. Improved mapping potential through optical-optical, optical-radar and radar-radar interoperability (refer to P1: Satellite sensor interoperability and complementarity). Key tasks include:

   - Assessment of key EO sensors regarding the achievable accuracy of time-series of annual forest area mapping, when using only core optical satellite sensors in the time-series (e.g. Landsat; Sentinel-2), versus replacing some of the Landsat scenes or individual pixels from data derived with alternative optical sensors (e.g. CBERS-4, RapidEye, AWIFS).
   - Assessment of achievable accuracies in time-series of annual forest area mapping, when interspersing core optical data-derived thematic products/scenes, with C- or L-band SAR-derived products/scenes.
   - Assessment of achievable accuracies in time-series of annual forest area mapping, when interspersing L-band SAR derived thematic products/scenes, with C- or X-band SAR-derived products/scenes.

iii. Assessment of the achievable forest/non-forest mapping accuracies using remote sensing data and according to national forest definitions.

iv. Use of older generation SAR data (e.g., ERS, JERS-1, ENVISAT ASAR) for generating a baseline for forest cover change.

(iii) Forest/Non-forest Change

NFMS Issue

To report on forest losses and gains and satisfy Approach 3 reporting, countries need to generate spatially explicit information on the changes in forest cover on an annual basis. Continuous forest measurement requires on-going access to a consistent time-series of remote sensing data. System performance is compromised through sensor failure, decommissioning of satellites and delayed launches of follow-on missions. Alternative data sources are often required to fill the gap for continuous forest monitoring.

Remote Sensing Considerations

Maps of forest cover change (both gains and losses) can be generated by aggregating the Land use change between forests and other land uses map, if available, or using a time-series of observations. When possible, change estimates should be based on direct classification of change data rather than post-classification comparison of two F/NF maps. Fire-related changes should be detected as distinct from other anthropogenic change.

Consistency between different satellite scenes at a given point in time is important for measuring change associated with forest cover loss. The need for consistency also translates to the overall system including ground sampling (e.g., continuous NFI). Medium resolution optical data has always driven the operational monitoring of forest cover change in the tropics. The integration of multi-sensor and/or multi-scale optical and SAR data can assist in resolving the ambiguities in forest cover change information, and fill the gaps in, and extend the data record for monitoring. There is potential to use dense time-series of C-band observations to detect forest cover loss under a forest mask, at a level comparable with that obtained using L-band SAR. Historic data can be used to generate a baseline for forest cover change mapping.

R&D Topics

The review found that Forest/Non-forest Change mapping was considered operational, with further R&D needed to understand the best use of data from optical and SAR systems for improved forest cover change monitoring, including:

i. Improvements in burned area mapping methods.

ii. Improved mapping potential through optical-optical, optical-radar and radar-radar interoperability (refer to P1: Sensor interoperability and complementarity). Key tasks include:

   - Assessment of key EO sensors regarding the achievable accuracy of time-series of annual forest/non-forest change area mapping, when using only core optical satellite sensors in the time-series (e.g. Landsat; Sentinel-2), versus replacing some of the Landsat scenes or individual pixels from data derived with alternative optical sensors (e.g. CBERS-4, RapidEye, AWIFS).
   - Assessment of achievable accuracies in time-series of annual forest/non-forest change area mapping, when interspersing core optical data-derived thematic products/scenes, with C- or L-band SAR-derived products/scenes.
   - Assessment of achievable accuracies in time-series of annual forest/non-forest change area mapping, when interspersing L-band SAR derived thematic products/scenes, with C- or X-band SAR-derived products/scenes.

iii. Optimising information extraction using dense time-series C-band SAR observations.

iv. Assessment of the ability to estimate annual change with acceptable accuracy.

v. Comparison of estimates of change obtained using post-classification comparison of two F/NF maps relative to estimates obtained using direct classification of change data.

vi. Identify in situ and VHR data needs and methods for calibration/validation of change products.

(iv) Near-Real Time Forest Change Indicators

NFMS Issue

Early warning indicators of potential changes in forest cover are not required for UNFCCC reporting, but may be needed when implementing REDD+. Rapid warning of new occurrences of change can assist in surveillance of illegal logging activity. To be of any use, monthly or better observations of forest cover change are required. Many countries do not have the capacity to process, in near-real time, the volume of data involved or validate the findings.

Remote Sensing Considerations

Coarse resolution EO data is sufficient for this product as it is not intended for quantitative analysis. This data can be sourced from satellites such as MODIS and PALSAR ScanSAR. High temporal frequency measurements, monthly or better, are required to detect rapidly occurring change. Targeted high resolution coverage can subsequently be acquired for validation and more detailed analysis where warranted. Intensive processing of hyper-temporal data requires efficient algorithms and computing power. Additional metrics, e.g., optically-derived spectral fractions, may improve the detection of disturbance pixels. The product is a first-cut attempt at identifying broad-scale change. As such, low accuracy is sufficient, however, methods of attributing accuracy to change pixels are required.

To achieve higher temporal frequency measurement (even daily), satellite observations are necessarily combined from several satellites operated by different countries. There are few nations with free-access policies however (i.e., public good satellites - Landsat, CBERS), and assembling the large datasets required for global monitoring would be prohibitively expensive [197]. Further discussion is needed on actual monitoring requirements and the optimal satellite configuration using existing and future/proposed optical and radar satellites (including constellations) for NRT forest change monitoring [196]. Establishing further links with government policy and taxpayer-funded satellites would require consideration.

R&D Topics

The review found that NRT Forest Change Indicators mapping was considered to be largely pre-operational, and so would benefit from additional R&D in the following areas:

i. Investigation of alternative data sources, e.g., Sentinel, PALSAR ScanSAR and TerraSAR-X.

ii. Development of rapid methods for NRT processing of time-series data that identify change pixels in consecutive images.

iii. Test different spectral fractions to identify disturbance pixels in different forest types and regions.

iv. Data and methods for attribution of uncertainty (e.g., low, medium, high) in each recorded change.

v. Determine data needs and best practice for calibration/validation, including regular ground measurements and VHR data.

vi. Determine optimal satellite configuration for NRT forest change monitoring using existing and/or future satellites (e.g., Sentinel series, NovaSAR, ALOS-2).

(v) Degradation Type map

NFMS Issue

An understanding of the type of degradation leading to the loss of biomass/carbon is required to manage forests and is a requirement for REDD+. Any type of degradation, e.g., selective logging, partial fire damage, pests/diseases, drought and fuel-wood collection, or proxies or indicators such as logging roads, vegetation index changes, changes in canopy structure, proximity to agricultural activity or infrastructure, should be taken into consideration and mapped if feasible.

Remote Sensing Considerations

Research is needed to identify the appropriate sensors and technologies for mapping the occurrence and type of degradation. Spatially explicit mapping of degradation type is needed for more accurate biomass/carbon estimation in specific forest disturbance classes. Consistent time-series data is required to identify change attributed to a particular type of degradation at the pixel level. The history of land use prior to, for example, abandonment to regenerating forest, can be retrieved from time-series data (e.g., Landsat). Knowledge of the land use history can inform on processes of degradation and change in the landscape, for example, changes in species dominance following clearing and re-clearing events. This may serve as a guide to adaptive management and targeted restoration of degraded forest communities.

Both optical and SAR data sources and LiDAR, used independently or in combination, are potentially useful for mapping degradation type. Testing of available methodologies to determine the most appropriate means of identifying degradation type is needed to advance the application to operational status. Optically-derived vegetation indices and spectral unmixing routines can be applied to separate forest and degraded classes where spectrally-distinct. SAR texture metrics and patterns associated with biomass strata may correlate with different types of degraded forest. Qualitative descriptors can be used, such as ‘mild’ or ‘heavily degraded’ forest for mapping purposes.

VHR data from optical or SAR data sources are needed for detection of degradation resulting from complete or partial removal (e.g., selective logging) of tree cover. Frequent satellite coverage and high geometric accuracy is a requirement. Change detection approaches can be adapted to use VHR data, taking into account shadow and mixed pixels that would otherwise obscure the detection of change. Automated tracking of change of a particular type of degradation requires further R&D. Feasibility will depend on what types of change are occurring in the area, and their manifestation and consistency in the imagery.

LiDAR is sensitive to various types of degradation because LiDAR measurements reflect the vertical distribution of biological material within a tree canopy. LiDAR is also sensitive to minor changes in biomass. It is therefore likely LiDAR has a great potential to discriminate between different types of disturbance events, including human induced degradation.

R&D Topics

The review found that Degradation Type mapping was considered to be in the R&D phase. The following topics are suggested for R&D to advance the capabilities for degradation type mapping:

i. Methods of extracting land use history (e.g., forest type and age, LULC transitions following clearing/re-clearing events) from time-series optical (e.g., Landsat) data.
ii. Integration of optical and radar data for identifying and mapping degradation type.
iii. Use of optically-derived fractional cover and spectral indices for classifying degraded and other forest classes.
iv. Evaluate change detection approaches using VHR data.
v. Development of automated methods for monitoring degradation type.
vi. Change detection and classification using LiDAR data (discrete and full waveform).
vii. Interferometric change detection in the 2D and 3D domain.

4.5 *Low Priority R&D*

Low priority R&D is required to research novel products (e.g., AGB estimates and Change in AGB) and other relevant issues (e.g., Socio-economic analysis) to support national forest monitoring systems and UNFCCC GHG emissions reporting. Two work packages are proposed: (P5) Improvements to GFOI Forest Map Product specifications, and (P6) Socio-economic analysis. P5 identifies specific R&D to advance forest map products (including AGB Estimates and Change in AGB) to operational status for inclusion in NFMS. P6 aims to support the assessment of socio-economic drivers of change in GFOI countries, to better understand the impact on GHG emissions and so devise strategies for mitigation.

R&D Package 5 (P5): Improvements to GFOI Forest Map Product Specifications

(i) Above-ground Biomass Estimation

NFMS Issue

Most approaches to biomass estimation require allometric models that relate biomass to forest structural parameters (e.g., tree height, trunk diameter, basal area). Allometric models are constructed using data obtained from destructive harvesting or from measurements of stem diameters for multiple heights for the same trees, and are typically acquired as part of local/regional forest inventories. Estimates for individual trees may be aggregated to obtain ground totals which then can be used with sample-based estimators to obtain large-area biomass estimates. Multiple approaches are being developed for estimation of above-ground live forest biomass (AGLB) from remote sensing data. The latter estimates may be better able to characterise large-area biomass distributions, and improve the precision of estimates of C stocks and GHG emissions.

Therefore the GFOI R&D program wishes to evaluate such techniques, and their routine applicability to a wider range of forest types/regions. Once validated across several sites in GFOI-associated countries and ecosystems, the research outcomes will be included in GFOI methodology and guidance documents. The countries can then draw on this to build their national carbon stock estimates. Ultimately, this should lead to more cost-effective use of the combination of ground based and remote sensing data for biomass estimation.

It should be emphasised that biomass estimation in this case is restricted to above-ground live biomass (AGLB) and not attempting to estimate other carbon pools. Research into the links with, and estimation of other pools, including below ground biomass, dead wood and decaying debris, is also a suggested GFOI R&D topic.

Remote Sensing Considerations

Multi-sensor satellite approaches (optical-SAR) combined with ground measurements and samples of airborne LiDAR strips show promise for precise estimation of AGB. Airborne LiDAR and SAR are currently the most promising technologies for precise AGB estimation. LiDAR is currently not sufficiently affordable to governments to acquire multi-year, wall-to-wall coverage for other than local REDD projects. However, experience from non-tropical forests with even a low sampling fraction shows that it is possible to obtain almost the same precision with only a sample of LiDAR data for a larger region as with a full wall-to-wall LiDAR survey. Further research is required on sampling designs and estimators for use of LiDAR in combination with wall-to-wall satellite data, especially SAR. Comparison and validation of different designs across various regions and continents is merited in order to reach general conclusions and recommendations and prepare for an operational phase.

The use of SAR is hampered by rapid saturation of the signal at low levels of AGB (wavelength dependent), precipitation and soil moisture effects, localised algorithm development and lack of consistency in estimates as a function of imaging parameters. Alternative approaches, including SAR interferometry (InSAR), polarimetric interferometry (POLInSAR) and combination of SAR and optical sensors may extend the saturation level for estimation of higher biomass forests.

The availability of forest canopy height would be of immense benefit in the estimation of forest AGB. Tree height and diameter are related to total biomass using allometric models. Coarse resolution height samples were acquired by the previous ICESat mission, and there will be future use of ICESat-2 data. Differencing the heights contained within a 'bare earth' DTM and canopy DEM yields a surrogate vegetation height, which can be used to estimate AGB. The problem is, satellite interferometric radars, such as TanDEM-X, only provide a first surface or canopy return, and the height of the ground underlying dense forest is not measured. Implementation of a correction factor using polarimetric information and LiDAR data is required for better estimation of actual forest height using these data. Bi-static SAR presents a novel approach to estimating forest height (and hence biomass) on a global basis, and is currently the subject of investigation.

R&D Topics

The review found that Above-Ground Biomass Estimation was considered to be in the R&D phase. The following R&D topics are suggested in order to evaluate the capacity for estimation of AGB using remote sensing:

i. Robust designs and estimators for the integration of optical, SAR and samples of LiDAR and field data for biomass estimation in different vegetation communities/forest structural types.

ii. Methods for the integration of LiDAR and optical data for calculating past emissions.

iii. InSAR and POLInSAR techniques using TerraSAR-X/TanDEM-X and future ALOS-2 data for tropical forest characterisation and biomass estimation.

iv. Determination of forest height from interferometric SAR data acquired by TanDEM-X.

v. Use of Bi-static SAR data from the TanDEM-X and simulated future L-band missions to estimate forest height, and associated accuracy when used as an input to biomass estimation.

vi. Comparison of, and uncertainty estimation in:

   - Tropical versus temperate and boreal forest biomass estimation (with same designs and estimators, i.e., transferability of methods).
   - Comparison and uncertainty estimation of airborne LiDAR with ground measurements, to provide faster and more cost effective in situ forest stratification and biomass estimation relative to traditional forest measurement.
   - End-to-end accuracy assessment/error propagation – from allometric errors and sampling to model calibration (remote sensing-to-field models).

vii. Consistent approaches to field sampling (sampling designs) to better meet the specific needs for ground data in estimation using remote sensing data.

viii. Determine the requirements of in situ data for calibration and validation of AGB retrieval methods using satellite data.

ix. Assess the relative contribution of uncertainty in individual tree allometric model predictions to the uncertainty in large-area biomass estimates.

x. Contribute to GlobAllomeTree, a tool developed by the FAO and partners for carbon stocks estimation (http://www.globallometree.org/).The database contains allometric equations in 57 countries in Africa, Europe and North America. Also contribute to further development of the IPCC-EFDB database on GHG emission factors (http://www.ipcc-nggip.iges.or.jp/EFDB/main.php).

xi. Establish the link between above-ground live biomass and other above-ground and below-ground carbon pools and emissions reporting.

(ii) Change in Above-ground Biomass

NFMS Issue

There are very few demonstrations of estimating change in above-ground forest biomass (AGB). Methods are being developed using multi-sensor approaches (e.g., LiDAR strips and SAR) combined with ground measurements to estimate AGB for one time period. Repeat acquisition of these data would facilitate estimation of change in AGB. Further research is required on methods for time-series estimation of AGB using repeat LiDAR strip samples and wall-to-wall SAR data. More accurate estimation of change in carbon stocks will improve the precision of GHG emissions estimates.

Remote Sensing Considerations

The current approach in the IPCC Guidelines is to monitor carbon stocks from ground measurements. Repeating these in situ measurements enables monitoring of AGB at two points in time, and hence assessment of change. Other carbon pools can similarly be measured. There are very limited remote sensing based examples of estimating change in AGB. Repeat acquisition of SAR data or airborne LiDAR, together with field plot data to calibrate models presents the best approach to estimating change in AGB over time. Consistent time-series of remote sensing observations is important for quantifying change.

Given the application of SAR and LiDAR to estimating biomass/carbon stocks, the aim of the R&D here is to devise consistent methods for the estimation of change in AGB over time.

R&D Topics

The review found that change in AGB estimation was considered to be in a very early R&D phase, with few, if any, studies conducted in tropical forests. Even in boreal and temperate zones, experiences with change in AGB are few and limited to narrowly focussed case studies. The following R&D topics are suggested in order to evaluate the capacity for estimation of change in AGB using airborne LiDAR and satellite data:

i. Different approaches for modelling and estimating change in AGB with LiDAR (direct versus indirect modelling and estimation).

ii. Modelling and estimation of change in AGB in tropical biomes and comparison with experiences from boreal and other forests (transferability of methods).

iii. Testing of LiDAR sampling designs, including combined use with complete coverage SAR, for AGB change estimation (corresponding to similar R&D topics for AGB estimation in the previous section).

iv. Further development of area frame sampling approaches, e.g., multi-stage inventory schemes with permanent sample plots [80]; [81] for calibration/validation.

R&D Package 6 (P6): Socio-economic analysis

NFMS Issue

As indicated by GOFC-GOLD, there is a need to understand the drivers of change leading to deforestation and degradation, and so devise strategies for reducing emissions [54]. The underlying causes of change are largely socio-economic, e.g., international markets, trade policies, technological change and population growth, with limited capacity for evaluation using remote sensing. However, there is potential to detect proximate drivers of deforestation and degradation (e.g., agriculture, mining and urbanisation), using remote sensing [124].

Therefore, GFOI wishes to support a complete assessment of socio-economic drivers of change in interested GFOI countries, to better understand the impact on GHG emissions and local livelihoods.

Remote Sensing Considerations

The drivers of forest area change are largely socio-economic, and difficult to determine by remote sensing. EO data can be used to derive proxies for deforestation and degradation however. As an example, large-scale clearing detectable by MODIS or Landsat-like sensors is a strong indicator of industrial rather than smallholder agricultural expansion as a deforestation driver [54]. How the drivers interact to induce land cover change at different spatial and temporal scales may not be well known however. It is anticipated that analysis of this data can assist development of tailored national strategies, linked with policy, for reducing emissions and increasing removals. The social factors, in particular, which are key to REDD+, are also difficult to characterise. More emphasis should be given to establishing the link between using EO data to enhance village livelihoods, for example.

Hierarchical modelling in Puerto Rico [125] provided a comprehensive understanding of the relative importance of various socio-economic (e.g., per capita income, population density and extent of protected areas) and biophysical factors (e.g., slope, soil quality and surrounding land cover) for forest transitions and the scales at which they are manifest. Studies of forest transition dynamics were considered important for decision making with regard to promoting forest conservation and regrowth at multiple spatial scales, and improving our understanding of how deforestation and reforestation drivers can change over time [125].

R&D Topics

Using the available remote sensing technology and methodologies for generating each of the forest map products, GFOI proposes to undertake a socio-economic analysis of the drivers of change in specific GFOI countries to determine:

i. The best- and worse-case scenarios for future deforestation and degradation at multiple scales.

ii. How these will impact on GHG emissions.

iii. The social factors and how EO data can be used to enhance village livelihoods.

iv. Strategies for reducing emissions and increasing removals and stabilization of forest carbon stocks, linked with national policy will be identified.

It is anticipated that the knowledge gained from these country-specific scenarios will serve as case study examples to other GFOI countries.

4.6 *R&D needs summary*

This section has identified a number of R&D topics for the purpose of (i) continuous improvement of GFOI operational product specifications, or (ii) methods development to advance products to operational status. Some topics are specific to individual GFOI forest map products; others relate to general methods improvement and consider cross-cutting issues that affect the accuracy of several or all of the GFOI products.

5 CONCLUDING SUMMARY

The GFOI R&D program will focus on helping countries establish long-term national forest monitoring systems through coordinated acquisition of complimentary earth observation data and advice on pre-processing methods for constructing consistent time-series for assessment of forest and land cover change. Prioritised R&D will ensure best use and best practice of improved practical forest measurement techniques, and data-model integration methodologies to enhance the functionality and/or accuracy of emissions reporting systems.

The GFOI Methods and Guidance Documentation [3] recommended seven thematic forest map products derived from remote sensing data for countries wanting to establish their national forest monitoring systems. Four supplementary products considered useful for NFMS and REDD+ reporting were also identified. The review considered the operational readiness of each of the forest map products. Table 11 presents a summary of the types of remote sensing data and their perceived operational status in estimating REDD+ activities [3]. Subsequent R&D required to meet immediate data needs and improve and/or advance the products to operational status was identified in a series of prioritised R&D Packages. A nominated GFOI Science Panel will be responsible for further review and implementation of the R&D packages.

Table 11. Summary of Types of Remote Sensing Data and their Perceived Operational Status in Estimating REDD+ Activities

Map number	Map Product	Coarse resolution optical	Medium resolution optical	High resolution optical	L-band radar	C-band radar	X-band radar	LiDAR
1)	Forest/Non-forest		Operational	Operational	Operational	R&D		
2)	Forest/Non-forest change		Operational	Operational	Operational	R&D		
3)	Forest stratification	Operational[8]	Operational[8]	Operational[8]	Pre-operational	R&D		
4)	All Land use categories		Operational[9]	Operational[9]	Pre-operational	R&D		
5)	Land use change between forests and other land uses		Operational[9]	Operational[9]	Pre-operational	R&D		
6)	Change within Forest land		Operational[8]	Operational[8]	Pre-operational	R&D		
7)	Near-Real Time Forest Change Indicators	Operational	Operational		Pre-operational	R&D	R&D	
	Training and/or verification of map products[10]			Operational				Operational

[8] Operational when stratification is limited between primary forest (PF) and planted forest (PlantF), but pre-operational if distinguishing between several sub-strata of natural forest.
[9] Annual mapping of All Land use categories and change at sub-hectare scales is considered technically feasible, but is yet to be implemented for use in greenhouse gas inventories.
[10] No associated map product.

Annex A IPCC Tier and Approach Concepts

Annex A.1 The IPCC Tier Concept relating to Emissions and Removals Factors

The following description is drawn from the GFOI Methods and Guidance Documentation [3].

An Emission Factor (EF) is defined as the average emission rate of a given GHG for a given source, relative to units of activity. A Removal Factor (RF) is the average carbon stock increase for a given source, relative to units of activity. Estimations of emissions and removals can be obtained in different ways. Therefore, the IPCC has classified the methodological approaches in three different 'Tiers', which vary according to the quantity of information required, and the degree of analytical complexity [1], [2].

Tier 1 employs the gain-loss method described in the *IPCC Guidelines* and the default EF/RFs provided by the IPCC. There may be simplifying assumptions about some carbon pools. Tier 1 methodologies may be combined with spatially explicit activity data derived from remote sensing.

Tier 2 generally uses the same methodological approach as Tier 1 but applies EF/RFs and activity data (AD) which are defined by the country. Tier 2 can also apply stock change methodologies based on NFIs. Country-defined EF/RFs and AD are more appropriate for the forests, climatic regions and land use systems in that country. Higher resolution AD are typically used in Tier 2 to correspond with country-defined coefficients for specific regions and specialised land-use categories.

At **Tier 3**, higher order methods are used including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution AD disaggregated at sub-national to fine grid scales. Properly implemented, these methods provide estimates of greater certainty than lower tiers and have a closer link between biomass and soil carbon dynamics. Such systems may be GIS-based combinations of forest age, class/production systems with connections to soil modules, integrating several types of monitoring. Areas of land where a land-use change occurs are tracked over time. In most cases these systems have a climate dependency, and thus provide estimates with inter-annual variability. Models should be well calibrated and tested.

Progressing from Tier 1 to Tier 3 generally represents a reduction in the uncertainty of GHG estimates through an increase in the complexity of measurement processes and analyses.

Annex A.2 The IPCC Approaches to Identifying Land Areas and Changes

The following description is drawn from the GFOI Methods and Guidance Documentation [3].

Approach 1 requires national estimates of the areas of different land use at different times but does not require information on the proportions of each type of land that were converted to another type of land use. This approach has severe limitations where there is significant land use change occurring, such as in many developing countries.

Approach 2 requires a land conversion matrix that indicates the area of each type of land use that was changed, and how this change was distributed amongst other land use types, but the explicit locations of change need not be provided.

Approach 3 requires spatially explicit time-series of land use and land use change, either by sampling at geographically located points, complete tally (wall-to-wall mapping) or a combination of the two. Approach 3 is in practice impossible without using satellite data.

Increased availability of remote sensing data makes Approach 3 (spatially explicit data) more accessible and it can in principle be used with any of the Tiers.

Annex B Selected Examples

Annex B.1 All Land Use Categories map

All Land Use Categories is a key product required for national baseline mapping. It is for participating countries themselves to decide what level of detail or classification scheme they wish to use. It is recommended that the scheme is compliant with the UN-FAO Land Cover Classification System (LCCS), while it should also allow aggregation into the six IPCC Land Categories, each with specific national definitions following the IPCC Good Practice Guidelines (Forest Land, Grassland, Cropland, Wetlands, Settlements and Other Land). Further division of the Forest Land category into sub-classes will be necessary to achieve the desired improved accuracy in the emission estimation. This includes distinction between natural and planted forests, as well as between forest types with different carbon stock levels, in conjunction with ground-based data.

Optical capabilities

Medium resolution 'Landsat-like' remote sensing data (30 m resolution) acquired on an annual basis with a minimum mapping unit (MMU) of < 0.5 ha is commonly used for land use categories mapping. Technical capabilities for the generation of All Land use categories products are well established using satellite optical data. Stand-alone product generation is feasible given at least one annual cloud-free coverage. Multi-season imagery has been shown to improve mapping outcomes [15]; [126]; [55]. In cases where data from a single year or a given season cannot be obtained, merging of datasets from a large time window, or using other sensors, will be necessary. The impact on the classification accuracy when using such (temporally/spatially) heterogeneous data sets needs to be quantified. A range of digital image classification and photo interpretation techniques are employed to produce All Land use categories products.

Global land use categories mapping is undertaken at coarser resolution (250-1000 m), for example, the European Commission Joint Research Centre (JRC) SPOT-4 VGT global land cover product for 2000 (http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php). GOFC-GOLD proposes land use mapping every 5 years, with periodic monitoring of regional forested areas at 25 m scales (http://www.fao.org/gtos/gofc-gold/cover.html),

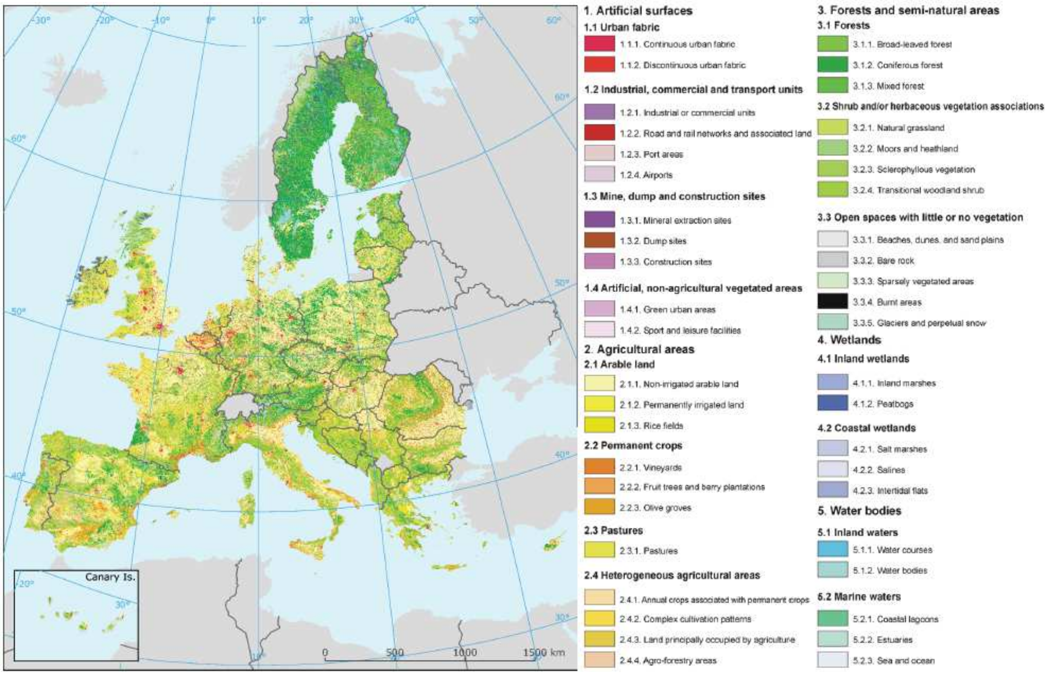
<u>National operational examples</u>

A number of national scale land cover programs utilising GFOI core and non-core data streams are currently operational.

- o South Africa's National Land Cover (NLC) program: Dominant land cover mapped in South Africa using dual-season Landsat-7 ETM+ (2000-2002, and subsequent imagery for 2009 update) and baseline photo-interpreted map [7].
- o Australia's National Carbon Accounting System (NCAS): Routine generation of country-wide LULC maps based on time-series processing of the Landsat archive (1972 to present; [82]; [6]).
- o India's national LULC program: Multi-temporal IRS-P6/Resourcesat-1 AWiFS data (since 2004/2005) used for rapid assessment of intra- and inter-annual LULC change at 1:250,000 scale (http://applications.nrsc.gov.in/default2.asp). IRS-1C/1D WiFS and MODIS images are used when cloud cover is limiting. LULC was classified using hierarchical decision tree, maximum likelihood and interactive techniques.
- o US National Land Cover Dataset (NLCD): 16-class land cover classification scheme applied consistently across all 50 United States and Puerto Rico [8]. NLCD2001 is based primarily on unsupervised classification of Landsat ETM+ circa 2001 data, and comprises land cover, percent developed impervious surface and percent tree

canopy density. Updates available for 2001 and 2006 (http://landcover.usgs.gov/uslandcover.php).

- European Copernicus Program (formerly Global Monitoring for Environment and Security; GMES, land monitoring service): Initial operations (GIO land; http://www.eea.europa.eu/themes/landuse/gio-land/gio-land) focused on pan-European land cover monitoring and an in situ component. Includes production of five High Resolution Layers (HLR) of the dominant land covers (artificial surfaces, forests, agricultural areas/grasslands, wetlands and water bodies) from 20 m satellite data, and for the reference year 2012. Combination of automatic processing and interactive rule based classification (http://land.copernicus.eu/pan-european). Final products are 100 m grid resolution. Currently in production, and yet to be verified.
- CORINE: pan-European LULC mapping (Figure 1) by photo-interpretation of time-series medium-high resolution satellite imagery [9]). CORINE Land Cover (CLC) products are based on Landsat-5 MSS/TM (CLC1990), Landsat-7 ETM (CLC2000), SPOT-4/5 and IRS P6 LISS III (CLC2006) and IRS P6 LISS III and RapidEye data (CLC2012 update). CLC uses a minimum mapping unit (MMU) of 25 ha (http://land.copernicus.eu/pan-european/corine-land-cover/view).



- **Figure 1 CORINE land cover mapping for the year 2000 using Landsat data [9].**

<u>Sub-national demonstrations</u>

There are a few examples of sub-national demonstrations of land use mapping reliant on Landsat data. The 30 m resolution is at the required scale for landscape management and decision making, and the free data access policy is of immense benefit to developing countries in implementing monitoring solutions.

- Africover Land Cover Classification System (LCCS): apriori classification and photo interpretation of Landsat TM imagery (1994 – 2002) and ancillary data. Land cover mapped at 1:200,000 scale (some at 1:100,000; http://www.africover.org/index.htm).
- North American Landscape Characterisation (NALC) project: Euclidean minimum-distance-to-mean clustering and classification of seven land cover classes using

Landsat MSS data for 1973, 1986 and 1991 for the mid-Atlantic region and San Pedro watershed [10].

There are many examples of sub-national demonstrations utilising GFOI non-core optical data streams (e.g., AVHRR, SPOT, ASTER and MODIS).

- UNEP's Environment Assessment Programme for Asia and the Pacific (UNEP/EAR AP): LULC mapped by unsupervised classification of NOAA AVHRR data and higher resolution Landsat TM and SPOT XS for hot spot investigations (http://www.rrcap.ait.asia/lc/cd/html/apn.html).
- Pan-European Land Cover Monitoring (PELCOM) project: Classification of major cover types using AVHRR data acquired in 1997 [11]. Pixels were assigned a class based on supervised clustering of NDVI composites, spectral distance and ratio metrics. Overall accuracy of 69.2 % compared to Landsat TM images.
- Northern Eurasia Land Dynamics Analysis (NELDA) project: Ensemble decision trees used to classify MODIS data from 2005 (http://www.fsl.orst.edu/nelda/ [12]. Training data sourced from Landsat imagery. Land cover accuracy ~73 %.
- Habitat mapping in Wales: Object-oriented rule-based classification of SPOT-5 HRG, ASTER and IRS LISS-III data (acquired over 2003 – 2006 [15]. 105 sub-habitats mapped with an overall accuracy of >80 %.
- Brazilian Legal Amazon: Land cover mapped at 1 km resolution using SPOT-4 VEGETATION data for 2000 and a probability-bagging classification tree [13]. Overall accuracy of 92 %.
- African ecosystems: Classification of ecosystems using SPOT VGT derived NDVI (2000-2007; [14]). Hybrid approach to classification comprising k-nearest neighbour (k-NN) clustering, hierarchical principles and Fast Fourier Transform (FFT). 73 classes mapped at an accuracy of 54 – 61 %.
- BOREAS project, Canada: Unsupervised clustering of monthly AVHRR-derived NDVI images (April – September 1992) to map seasonal land cover. Final class labelling used field data and Landsat TM images (http://daac.ornl.gov/BOREAS/boreas.shtml).

<u>Promising R&D case studies</u>

R&D has addressed approaches to mapping seasonal land use categories, gap-filling and sensor interoperability.

- Baltic Sea drainage basin: Unsupervised classification and clustering of IRS-1C/D WiFS images (1997-2000; [20]). MODIS data used to fill gaps in WiFS data.
- Chiapas State, Mexico: Comparison of optical (RapidEye, Landsat TM) and SAR (ENVISAT ASAR, ALOS PALSAR) data for land cover classification [219]. Higher mapping accuracy obtained using optical data. Limited difference between optical and SAR results when L-band SAR was used.
- EU Project ReCover, Chiapas, Mexico: Wall-to-wall REDD monitoring services demonstrated using optical (Landsat, RapidEye) data [220]. VHR optical data used in cal/val of models and results. Overall accuracies for classification of six IPCC land cover classes ranged from 93.8 – 94.3 % using RapidEye, and 88.3 – 90.9 % using Landsat. Mapping accuracy was around 7.6 % lower than for F/NF classifications. The high proportion of forest cover contributed to the high overall accuracy. Lower forest cover would have reduced the accuracy due to confusion in non-forest (grassland and cropland) classes.

- o Savannakhet province, central Laos: Combination of 1 % VHR optical data (Quickbird-2 and Kompsat-2) and medium resolution (ALOS AVNIR-2) wall-to-wall mapping in a statistical sampling framework for mapping tropical forest classes [221]. Unsupervised fuzzy classification of AVNIR-2 data resulted in an accuracy of 19 – 91 % in the 6-class case over VHR image areas. The area of natural forest was over-estimated and disturbed forest was under-estimated. Sources of confusion included mixed non-forest classes (e.g., cleared forest and farmland), and forest and shrubland.

Radar capabilities

Given the superior spectral information afforded by optical sensors, these data are typically preferred for land use categories mapping. In tropical countries frequented by heavy cloud cover however, it is difficult to obtain the consistent cloud-free images required for monitoring. SAR's cloud-penetrating and all-weather imaging capability present an alternative means of extracting detailed information on land cover. Suitably calibrated data are required, including corrections for terrain slope (requiring a high resolution DEM). Dual (wet) season coverage can improve the discrimination of certain vegetation classes, and in particular, flooded vegetation [127]. Some countries already have expertise in processing radar data. Countries with limited expertise should focus on using available optical data and then consider the synergy with radar.

Stand-alone product generation is possible using dual polarisation SAR, but class separability is generally lower than for optical data. Longer wavelength (L-band) SAR is preferred given the high sensitivity to forest structure and biomass and deeper penetration of the canopy [209]. Shorter wavelength (C- and X-band) data is typically insufficient on its own for All Land use categories mapping [128]; [129]. There is more rapid saturation of the signal with increasing forest biomass at shorter wavelengths. The use of multiple polarisations, dense time-series, or synergistic use with lower frequency SAR or optical data is necessary [205]; [206]; [207]; [208]; [210]. Studies have also shown that the combination of L-band or C-/X-band and optical data can improve the mapping of certain cover types [21]; [22]; [23].

With an increasing number of SAR satellites (including L- and P-band missions) proposed for launch over the next few years and more systematic acquisition of SAR data, there are increasing opportunities for generation of country-wide land use categories maps and detection of change. Full polarimetric and interferometric capability will boost the information content and discrimination of land use classes. Pan-tropical, 50 m orthorectified ALOS PALSAR mosaics produced as part of JAXA's ALOS Kyoto &Carbon Initiative project (http://www.eorc.jaxa.jp/ALOS/en/kc_mosaic/kc_mosaic.htm; [167]) provide a valuable data source for global forest and land use categories mapping. The launch of ALOS-2 in early 2014 will ensure on-going acquisition of data suited to this task.

<u>Sub-national demonstrations</u>

Demonstration of the utility of SAR for All Land use categories mapping at sub-national scale was implemented within the GEO FCT program. Mapping accuracy using the PALSAR data exceeded that of previous Landsat derived land use categories maps. Ambiguities in certain classes could be resolved through the combination of PALSAR and optical (e.g., MODIS) or other SAR data [16].

- o Borneo LULC: Land cover mapped by unsupervised mixture modelling and Markov Random Field (MRV) classification of ALOS PALSAR Fine Beam Single (FBS) and Fine Beam Dual (FBD) data (Figure 2; [18]). Overall accuracy of 85.5 % for 18 classes [16]. Mapping accuracy exceeded that of previous Landsat-derived LULC maps. Combination of time-series PALSAR and ScanSAR data and other optical (e.g., MODIS) data might improve mapping accuracies.

- Tasmania LULC: Extraction of wall-to-wall forest and land cover by object-oriented rule-based classification of ALOS PALSAR FBD data (2007-2010; [17]). Cover classes identified using field data and available state-wide vegetation mapping. Overall mapping accuracy ~82.3 %.
- Central Siberia LULC: A SAR processing chain was developed to map LULC in Central Siberia using ALOS PALSAR FBD strip data [19]. A multitemporal approach to classification was applied that accounted for temporal backscatter variations in land cover classes. Interferometric coherence was also calculated and used together with intensity data in a nearest neighbour algorithm to classify ten cover classes.

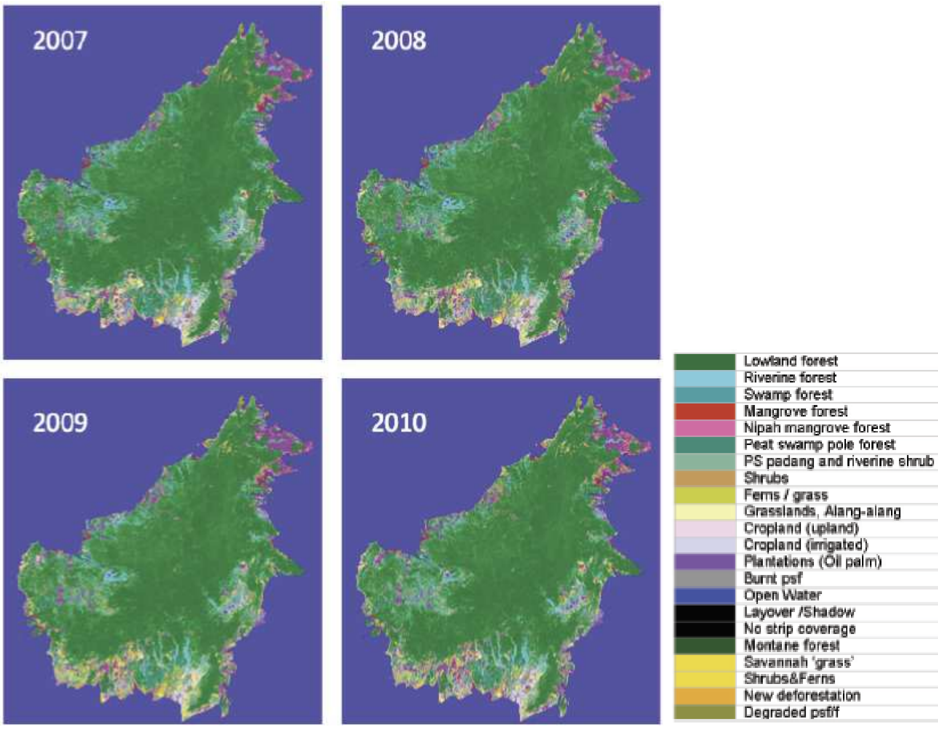


Figure 2 Thematic maps of Borneo derived from ALOS PALSAR FBS and FBD strip data, 2007 - 2010 ([18]; http://www.geo-fct.org/pd-team-documents).

Promising R&D case studies

A handful of R&D case studies have demonstrated the potential for improved land use categories mapping using multiple polarisation, shorter wavelength SAR data (e.g., X-band).

- Acre State, SW Brazilian Amazon: Dual polarimetric TerraSAR-X Stripmap data used to classify primary forest, degraded forest, pasture and bare soil [205]. Maximum Likelihood (MLC) and Iterated Conditional Modes (ICM) were applied to Lee filtered data. The inclusion of entropy derived from the Cloude decomposition was significant in the separation of classes. The overall classification accuracy was 76 % with a Kappa value of 0.67. Primary forest was separable from pasture and bare soil, however, confusion was observed with degraded forest.
- Bwindi Impenetrable National Park, Uganda: Comparison of land cover mapping accuracies using quad-polarised ALOS PALSAR and dual-polarised TerraSAR-X data [206]. Pixel-based classification of polarimetric bands and derived texture metrics was implemented using the decision tree method. Classification using only TerraSAR-X polarimetric bands (HH, VV and HH/VV) resulted in Kappa statistics of 0.43, 0.36 and 0.47 respectively. The inclusion of texture metrics derived from TerraSAR-X HH polarisation data, resulted in Kappa statistics of 0.67, 0.67 and 0.72 respectively. Classification using PALSAR polarimetric bands (HH, HV, VV, HH/HV, VV/HV,

HH/VV, HH/HV/VV and HH/HV/VH/VV) resulted in Kappa statistics of 0.3, 0.34, 0.33, 0.71, 0.71, 0.47, 0.73 and 0.72 respectively. The results support the notion that high (multiple) polarisation increases land cover classification accuracy, and the inclusion of SAR-derived texture can improve land cover identification and mapping. The use of cross-polarised channels was essential for high classification accuracy.

- South Kalimantan, Indonesia: Classification of Cloude and Yamaguchi decomposition parameters derived from quad-polarised TerraSAR-X Stripmap data for mapping land cover [207]. Training data for several classes was identified using forest inventory, and used to determine the statistical separability of derived polarimetric features. Separability analysis was applied to both amplitude and polarimetric features using the Wilk's Lambda and Transformed Divergence measures. The use of polarimetric features greatly assisted in the interpretation of the imagery and increased the statistical separability of classes. In the Cloude decomposition, Entropy and Alpha features enhanced class separability, with high values for regrowth, and distinct values for forest and wetlands. In the Yamaguchi decomposition, wetlands and flooded vegetation were easily identified by double bounce scattering, and volume scattering increased with increasing vegetation volume from grassland to shrubland to secondary forest. The combination of double bounce, single bounce and Alpha features explained most of the variance in the data.
- Munich and Pforzheim test sites, Germany: Classification of forest and other land cover using high resolution TerraSAR-X Spotlight mode (HH and VV) data and logistic regression models [208]. Mean and standard deviation of the backscatter were useful measures for discrimination of classes. The HH polarisation image was better suited to classification of urban areas, and the VV polarisation image was better suited for agricultural areas. The combination of polarisations led to improved classification accuracy. The inclusion of terrain slope also improved the classification. An overall classification accuracy of 92 - 95 % was achieved. Mapping accuracy decreased by 7 - 9 % when the model developed for the first site was applied to the second site.
- Peat swamp forest, Central Kalimantan: Comparison of TanDEM-X monostatic and bistatic mode data (Stripmap, X-HH) for classification of forest and other land cover classes in a tropical peatland [210]. Training and validation data were sourced from field data and aerial photographs. An object-based maximum likelihood classifier was applied. Interferometric coherence significantly improved the separability of land cover classes, compared to the monostatic dataset. Bistatic coherence was largely determined by volume decorrelation of forest canopy constituents, and contained much information about canopy structure. The bistatic scattering coefficient had limited influence on class separability however. Classification using coherence and texture outperformed classification using the monostatic scattering coefficient and texture by more than 10 %, with an overall accuracy of 85 %.
- EU Project ReCover, Chiapas, Mexico: Wall-to-wall REDD monitoring services demonstrated using SAR (ALOS PALSAR) data [220]. VHR optical data used in cal/val of models and results. Overall accuracy for classification of six IPCC land cover classes was 89.1 % using ALOS PALSAR.

Interoperable capabilities

Further R&D of the potential synergies of optical and SAR data for improved land use categories mapping is needed. Optical and SAR sensors observe the surface differently and so strategies that maximise the sensitivities of each data source for optimal discrimination of land cover are required.

Sub-national demonstrations

- o Malawi: LULC mapped using interferometric ALOS PALSAR FBS/FBD, multitemporal ENVISAR ASAR AP, Landsat-5 TM and Landsat-7 ETM+ data [159]. A knowledge-based approach to classification was implemented that exploited the interferometric, multi-temporal intensity and spectral signatures. Data fusion and change detection were also applied to generate LULC change data. Product reliability was estimated at 80 %. Classification errors were highest in mixed classes, e.g., cropped areas <1 ha in size.

Promising R&D case studies

In heavily cloud-affected regions, accurate mapping of land use categories would be difficult using optical data alone. The inclusion of elevation and slope often reduces the confusion between cover types [21]. Texture, relative to SAR resolution, can improve the discrimination of classes [22]; [23].

- o Northern Thailand: Maximum likelihood classification of Landsat TM, ALOS PALSAR and ASTER DEM improved the separation of evergreen and deciduous forests from other vegetation, urban villages and fallow fields in a tropical mountainous area [21].
- o Bangladesh: Transformed Divergence (TD) measures calculated using fused radar and optical data to determine best band combinations for classification of LULC [22]. SIR-C L-band performed slightly better than C-band, however, no single polarisation provided consistently higher TD values. Further investigation of the value of radar texture and sensor fusion was recommended.
- o Boston, Massachusetts: Random Forest classification of multi-season Landsat ETM+ and single-season ALOS PALSAR data [23]. 17 classes mapped at accuracies of 31 % (PALSAR-only), 72.3 % (PALSAR and texture), 78 % (single-date Landsat), 86.9 % (multi-season Landsat), 92.7 % (multi-season Landsat and texture), and 93.8 % (combined Landsat and PALSAR).
- o West Africa: Maximum Likelihood and Neural Networks classifiers applied to Landsat TM and AVNIR-2 and PALSAR onboard ALOS to map land cover [24]. High accuracies were achieved from the combined SAR-TM (91-93 %) and SAR-AVNIR (96-98 %). Optically derived texture was critical to class discrimination.
- o EU Project ReCover, Chiapas, Mexico: Wall-to-wall REDD monitoring services demonstrated using the combination of optical (Landsat) and SAR (ALOS PALSAR, ENVISAT ASAR) data [220]. VHR optical data used in cal/val of models and results. Overall accuracy for classification of six IPCC land cover classes was 91 %.

Annex B.2 Land Use Change between Forests and Other Land Uses (Activity Data)

In order to calculate the net carbon emissions, countries are required to produce *activity data*, i.e. information about the extent of REDD+ activities. Conventionally activity data are areas arranged in a land use change matrix (Figure 3) sufficiently disaggregated so that they can be associated in an emissions or removal calculation with carbon stock differences or other *emission factors* which are usually expressed per unit area.

A larger number of land cover/land use classes will result in a more complex transition matrix, but accommodate country specific change classes of relevance to emissions reporting. Additional separation into further sub-classes is particularly desired for the "Forest-remaining-Forest" transition class to accommodate the characterisation of changes in the carbon contents within a forest, e.g., as a result of degradation (e.g., selective logging, fragmentation, fires, deceases) and/or forest management practices (e.g., thinning, carbon enhancements). The Forest-remaining-Forest change category should cover transitions between those forest sub-classes and the times since the changes.

	Forest land	Grassland	Cropland	Wetlands	Settlements	Other land
Forest land	FF (+)	FG	FC	FW	FS	FO
Grassland	GF	GG	GC	GW	GS	GO
Cropland	CF	CG	CC	CW	CS	CO
Wetlands	WF	WG	WC	WW	WS	WO
Settlements	SF	SG	SC	SW	SS	SO
Other land	OF	OG	OC	OW	OS	OO

Figure 3 Transition Matrix showing the IPCC land cover categories and associated transitions. Additional subcategories within the FF transition class (Forest-remaining-Forest) will be required to categorise, e.g., degradation, enhancements of carbon stocks and transitions from natural forest to plantations.

Optical capabilities

Multi-year time-series optical data are required for the generation of the Land Use Change between Forests and Other Land Uses products. Approaches to change detection and multi-temporal analyses are reasonably well established, but with the opening up of the Landsat archive, novel methods of utilising the extensive time-series are required.

National operational examples

- Australia's NCAS: Country-wide land cover change maps produced routinely using the Landsat archive [82]; [6]. The high co-registration accuracy and radiometric consistency makes it possible to drill through the time-series and evaluate land cover change on a pixel-by-pixel basis. Continuous improvement is anticipated as new data becomes available (e.g., high resolution DEMs and hyperspectral data) and methods for their integration are developed.
- CORINE: Land cover change mapping between 1990 – 2000, 2000 – 2006, and 2006 – 2012 [9]. Threshold for detection of change is 5 ha (http://land.copernicus.eu/pan-european/corine-land-cover/view).

Promising R&D case studies

R&D studies utilising GFOI core (e.g., Landsat in the Amazon) and non-core (e.g., MODIS in Bolivia) data streams have investigated various approaches to change detection and classification for land use change monitoring. Various collaborations with INPE, Brazil, have used time-series Landsat data to quantify the loss of natural vegetation (Figure 4; [25]), quantify deforestation and regrowth and the extent of burned areas [26], and identify and map land degradation risks and change [27].

- Mato Grosso region, Brazil: Maximum likelihood classification and change detection of Landsat data (1985-2005) to quantify loss in vegetation cover (Figure 4; [25]). Map accuracy was > 85 %.
- Acre State, Brazil: Land cover change determined by classification of Landsat MSS and TM derived fraction images (1980, 1990 and 2000), and MODIS data (2005 and 2007; [26]). The multi-temporal processing methodology is proposed for inclusion in the DETER and PANAMAZONIA operational systems.
- Western Amazon: Maximum likelihood classification and spectral mixture analysis (SMA) to map land cover [27]. Accuracy of change results was 85 %. Increasing the temporal resolution of the satellite data would avoid biases caused by seasonal variations.
- South eastern Bolivia: Supervised decision tree classification of MODIS data (1994-2008) to map agricultural land use [28]. High overall accuracies achieved (91.6-93 %). Areas of forest to agriculture extensification and intensification of pasture and cropland regimes were mapped in the process.

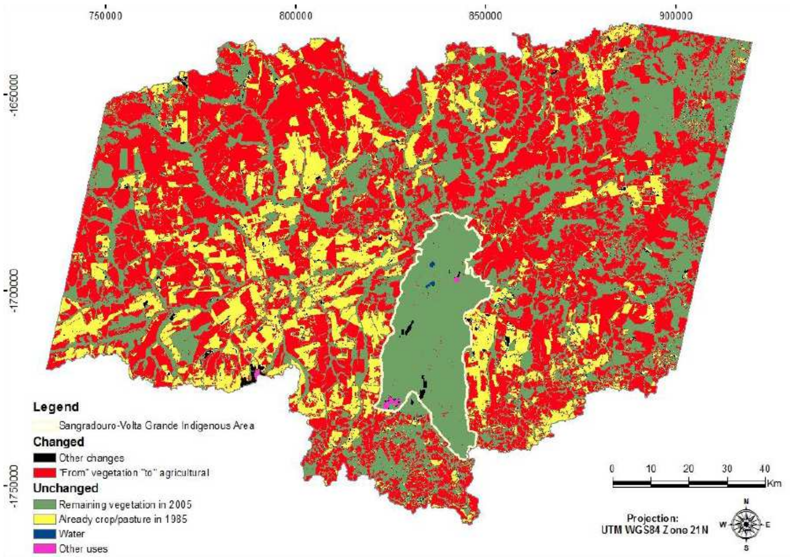


Figure 4 LULC change map for the 1985 – 2005 period for the Mato Grasso region, Brazil [25].

Radar capabilities

Sub-national demonstrations

There are few sub-national demonstrations of land use change mapping using radar.

- Tasmania: LULC change maps produced using time-series ALOS PALSAR data [17]. The change maps summarise the spatial extent and location of deforestation, regeneration and no change on an annual timescale for 2007 – 2010.

Interoperable capabilities

The integration of various combinations of optical and SAR data can improve mapping of land use change. Interoperability in this case refers to the use of multi-scale optical data, multi-frequency radar data, and SAR-optical integration for improved land use change mapping. The latter exploits the texture and polarimetry of radar and unique spectral response in optical data for greater class separability and hence more accurate detection of change.

Promising case studies

- Haihe River, China: Object oriented classification of SPOT-5 and RADARSAT-1 data to map LULC change [29]. Multi-scale and multi-texture fusion improved the separation of classes and identification of change.

Annex B.3 Evaluation of operational status: Land Use and Change

Table B.1 Evaluation of operational readiness of GFOI Land Use and Change information products.

Code	National operational examples	Sub-national demonstrations	Promising R&D case studies	EO data availability	Additional R&D needs	GOFC-GOLD Reference
All Land Use categories	-NLC, S. Africa -NCAS Australia -Copernicus, pan-European -CORINE, pan-European	-Africover -NALC, USA	- Mexico - EU ReCover	**Core:** Landsat-7 Landsat-5	- Cloud-filling methods - Optical-radar synergy - Integration of satellite & ground data - Integration of seasonal data - SAR interoperability - Data fusion techniques - Accuracy of global products	
	-LULC, India -CORINE, pan-European **GLOBAL:** -JRC GVM	-UNEP/EARAP (Asia) -Wales habitat -PELCOM (Europe) -NELDA (Europe) -African eco's -BOREAS, Canada -FCT Borneo -FCT Tasmania - Central Siberia - Malawi	- Baltic - EU ReCover - Laos - Mexico - SW Brazilian Amazon - Uganda - Kalimantan, Indonesia - Germany -Thailand -Bangladesh -Boston -West Africa	**Non-core:** IRS WiFS IRS P6 LISS III ALOS PALSAR ALOS AVNIR-2 RADARSAT-2 ENVISAT ASAR TerraSAR-X TanDEM-X SPOT-4/5 RAPIDEYE NOAA AVHRR ASTER MODIS SIR-C JERS-1		
Land Use Change between forests and other land uses (Activity Data)	-NCAS Australia -CORINE, pan-European		-Amazon	**Core:** Landsat-7 Landsat-5	- Country specific transition classes - Temporal processing methods - High resolution DEMs - Data integration - Future hyperspectral data	- Relating land use conversion to emissions estimation, carbon transfers between pools
	-CORINE, pan-European	-FCT Tasmania	-Bolivia - Haihe R, china	**Non-core:** MODIS ALOS PALSAR SPOT-4/5 RAPIDEYE IRS P6 LISS III RADARSAT-1		

Annex B.4 Forest/Non-Forest

The Forest/Non-Forest (F/NF) Cover product map can be generated independently or derived by aggregating the Land Use/Land Cover product, if available. For REDD+ reporting, plantations should preferably be classified as a separate class within Forest. Technical capabilities for derivation of F/NF and forest/non-forest cover change are well advanced using both optical and SAR remote sensing data and at regional, national and global scales. Robust and consistent methodologies facilitate accurate and repeatable forest area mapping.

Optical capabilities

Optical data can be used stand-alone if cloud-free coverage is obtained. At least one annual national coverage is required; dual-season or better is preferred.

National operational examples

National operational programs for mapping F/NF cover are implemented using both GFOI core (e.g., Landsat in Australia's NCAS) and non-core (e.g., IRS in India's National Forest Inventory) data streams.

- Australia's NCAS: Routine generation of country-wide forest extent maps, based on time-series processing of the Landsat archive [82]. Thresholds are applied to produce single-date forest cover probability images.
- NCAS Australia is assisting in the development of INCAS, a national scale, operational forest monitoring system using satellite data in Indonesia. Time-series Landsat imagery and forest inventory are the driving forces of the system.
- National Forest Inventory, India: Forest cover and carbon stock change is assessed on a 2-year interval (since 1987) using Landsat MSS/TM imagery and IRS-1B/1C/1D/P6 LISS-II/III data [30]. MMU: 1 ha (1:50,000 scale). Forests are classified in four categories relating to density.

Sub-national demonstrations

There are several examples of sub-national demonstrations of forest/non-forest cover mapping using medium resolution optical data.

- Xingu Basin, Brazilian Amazon: Segmentation and Random Forest classification of Landsat-5 TM data (June-August 2007) to map F/NF cover [31]. All images acquired during dry season to minimise cloud cover. Overall accuracy of 94.6 %.
- Queensland Statewide Land Cover and Trees Study (SLATS): Threshold of 20 % applied to Landsat-derived Foliage Projective Cover (FPC) to map forests and woodlands (http://www.derm.qld.gov.au/slats/). LiDAR validation of models reveals overall RMSE of <10 % [32]. Similar methodology can be applied to high resolution SPOT-5 imagery for fine-scale mapping of riparian and remnant vegetation.
- European Russia: Supervised Classification And Regression Tree (CART) applied to time-series Landsat data (2000 – 2005) to map boreal forest cover and gross loss [33]. Training data extracted from Landsat and Quickbird data and aerial photographs. Good agreement between forest cover estimates and Landsat data (89 %).
- EC JRC Pan-European forest cover maps: Multi-scale data fusion and neural network clustering of IRS-P6 LISS-III and MODIS data to map F/NF cover for 1990, 2000 and 2006 at 25 m spatial resolution [34]. Overall accuracy of 88 %. Improvements may be gained through the inclusion of meteorological and DEM data.

- Forest cover, Europe: Bayesian maximum likelihood classification of AVHRR data (summer acquisitions, 1990-1992; [35]. Overall accuracy of 82.5 % compared to Landsat MSS data.

<u>Promising case studies</u>

- EU Project ReCover, Mexico, Guyana, Democratic Republic of Congo, Colombia, Fiji: Wall-to-wall REDD monitoring services demonstrated for five study sites using optical (Landsat, RapidEye) data [220]. VHR optical data used in cal/val of models and results. F/NF mapping accuracies ranged from 86.7 – 93.8 % using RapidEye (DRC and Mexico), and 91.7 – 93.4 % and 96.9 % using Landsat (DRC and Fiji), and 84.5 % using ALOS AVNIR-2 (DRC). Similar mapping accuracies were obtained despite different input data and image interpretation approach.
- Savannakhet province, central Laos: Comparison of optical (ALOS AVNIR-2) and SAR (ALOS PALSAR) data for mapping tropical forest cover [221]. Method combines 1 % VHR optical data (Quickbird-2 and Kompsat-2) and medium resolution wall-to-wall mapping in a statistical sampling framework. Unsupervised fuzzy classification of AVNIR-2 data resulted in an accuracy of 68 – 97 % over VHR image areas. The study concluded that optical data should be used as the primary data source as it provides a higher number of predictor variables than mono-temporal SAR and the results are less dependent on vegetation structure.

Radar capabilities

L-band SAR can be used stand-alone if dual-polarisation is obtained. The cross-polarisation channel is sensitive to vegetation structure. At least one annual coverage (dry season) is required. Dual-season or better and the combination of SAR and optical data provide improved classification accuracy. C-band SAR is generally not sufficient on its own. The combination of C- and L-band SAR can improve class distinction. Dual polarisation data is required for this purpose.

<u>Sub-national demonstrations</u>

Under the GEO FCT program, a number of sub-national demonstrations have highlighted the effective use of SAR for wall-to-wall F/NF cover mapping. In particular, L-band SAR (e.g., ALOS PALAR) provides an accurate source of spatially explicit information on forest cover.

- Mexico: Forest probability mapping using ALOS PALSAR data for 2008 (Figure 5; [18]). Validation underway.
- Xingu basin: Complementary forest cover maps produced using ALOS PALSAR data (Figure 6; [31]). The inclusion of spatial (e.g. object length, width and area) and topographic (e.g., mean and standard deviation SRTM elevation) features improved class discrimination. F/NF mapping accuracy of 92.4 %.
- Tasmania: Time-series LULC maps generated using ALOS PALSAR data were aggregated to produce maps of F/NF cover [17]. F/NF mapping accuracy of 92.1 %. LULC maps derived from RADARSAT-2 Wide Beam 3 (C-band VV and VH) data were similarly aggregated to produce F/NF. The scale and accuracy of mapping is appropriate to regional scale forest monitoring for the purposes of MRV and national carbon accounting.

<u>Promising case studies</u>

- EU Project ReCover, Mexico, Guyana, Democratic Republic of Congo, Colombia, Fiji: Wall-to-wall REDD monitoring services demonstrated for five study sites using SAR (ALOS PALSAR, ENVISAT ASAR) data [220]. F/NF mapping accuracies ranged from 88.5 – 89.1 % using ALOS PALSAR (DRC and Mexico) and 88.7 % using

ERS/ENVISAT ASAR (DRC). The L-band SAR results were comparable with those obtained using optical data.

- o Savannakhet province, central Laos: Comparison of optical (ALOS AVNIR-2) and SAR (ALOS PALSAR) data for mapping tropical forest cover [221]. Method combines 1 % VHR optical data (Quickbird-2 and Kompsat-2) and medium resolution wall-to-wall mapping in a statistical sampling framework. Unsupervised fuzzy classification of ALOS PALSAR data resulted in an accuracy of 46 – 79 %. Performance was lower than for optical data. The shrub cover and scattered trees increased the difficulty of mapping using mono-temporal SAR imagery. A combination of optical and SAR data for forest cover mapping was recommended.

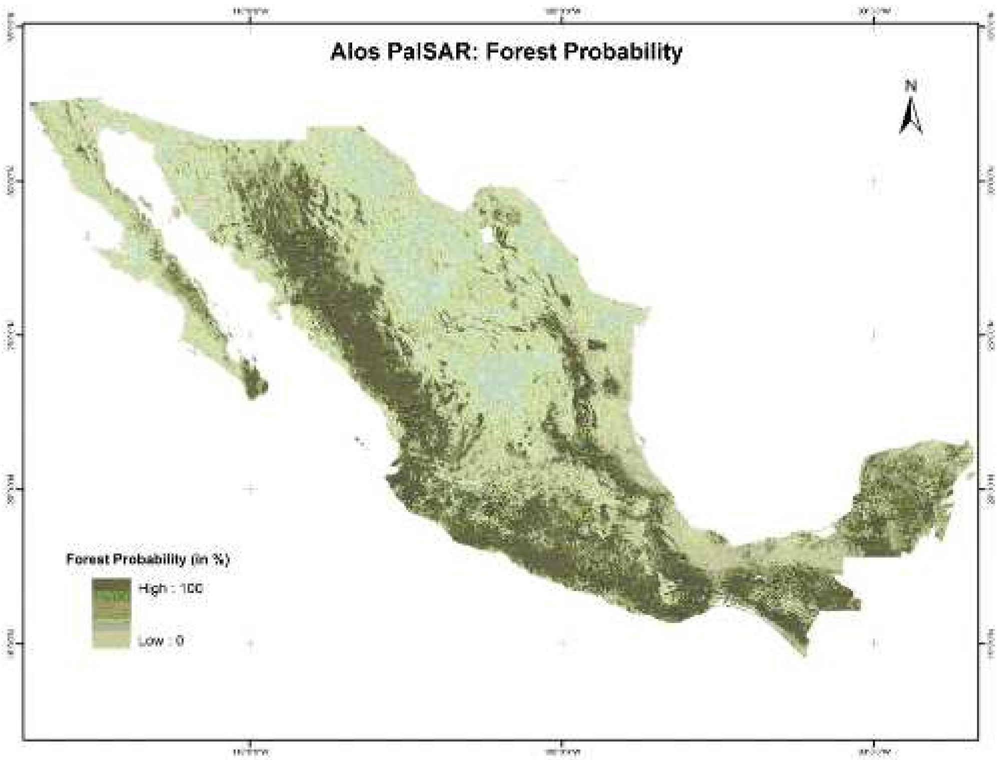


Figure 5 Forest probability map for Mexico derived from 2008 ALOS PALSAR data ([18]; http://www.geo-fct.org/pd-team-documents).

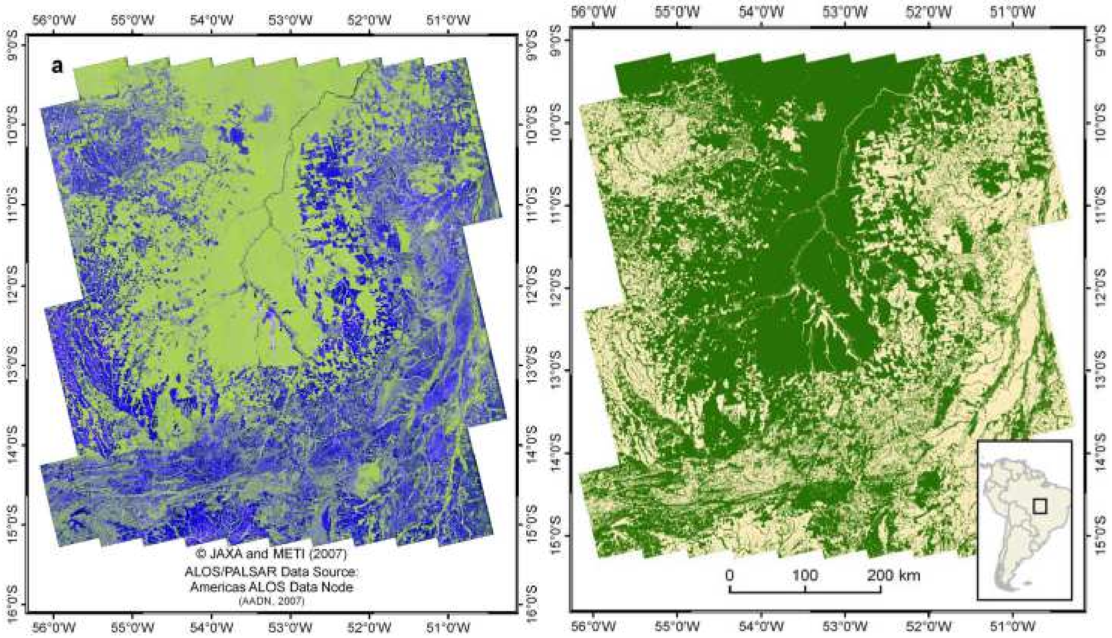


Figure 6 Satellite mosaic for Xingu River Basin, Brazilian Amazon, generated using ALOS PALSAR data (HH/HV/HH-HV in RGB, left), and derived forest/non-forest map (right; [31]).

Interoperable capabilities

The integration of multi-scale or multi-sensor remote sensing data can improve the discrimination and mapping of F/NF. The integration of optical and radar data exploits the chemistry, colour and underlying moisture content of the forest, together with the structure, density and dielectric properties for improved classification of forest cover [130]; [53]. The interoperable use of optical and radar data is not common however, and only few case studies have demonstrated the potential improvements afforded by their synergy [36].

Promising case studies

- North-east Tasmania: Canonical Variate Analysis used to determine class separability in Landsat TM and ALOS PALSAR data and derive inputs to maximum likelihood classification of F/NF [36]. Best accuracy was obtained from joint processing (94.3 %). PALSAR HV was critical to F/NF discrimination in the PALSAR.
- EU Project ReCover, Mexico, Guyana, Democratic Republic of Congo, Colombia, Fiji: F/NF mapping accuracy of 96.9 % achieved by feature-level fusion of ALOS PALSAR and Landsat data in Guyana [220].

Annex B.5 Forest/Non-forest Change

This product is a map of changes in forest cover. Typically to be generated on an annual basis to accommodate reporting of forest losses and gains. Forest/Non-forest Change can be derived by aggregating the Land use change between forests and other land uses product, if available, or generated using a time-series of satellite data (caution: Forest/Non-forest Change should not be derived by taking the difference between two Forest/Non-Forest Cover maps, as classification errors in each of the maps will result in false forest changes in the change product). Fire-related changes are important to detect and can e.g. be derived from lower resolution operational products such as MODIS burnt area maps.

A Historical Forest/Non-forest Change map can be useful to determine past forest cover baselines and assess historical change and trends. This product is the same as Forest/Non-forest Change, but is derived from historical (archived) optical or SAR satellite data. The accuracy of the historical change product can be expected to be lower than Forest/Non-forest Change due to inconsistent archive data. However improved accuracy may be achieved by “pixel mining”, i.e. multi-temporal compositing of cloud-free pixels in archived optical data, even scenes with cloud cover up to 80-90%.

Optical capabilities

Medium resolution optical data is currently the primary data source for monitoring forest/non-forest cover change in the tropics [37]. Use of a consistent time-series of observations is critical to obtaining accurate results for assessing longer term forest area change [44]; [131]; [132]; [43].

Optical data can be used stand-alone if cloud-free coverage is obtained. Time-series, multi-year coverage is preferable, as intra-year data improves classification accuracy. The scale and rate of change in forest cover affects its detection using optical satellite data. Obvious changes in forest extent due to clearing or conversion to other land uses can be detected using time-series observations from medium (e.g., Landsat, SPOT-5) to coarse (e.g., MODIS, MERIS) resolution optical data. Bi-annual and annual observation of change is possible over long time-scales. Coarse resolution data can also be used to locate hot spots for more detailed analysis using high resolution data. More subtle changes in forest cover require more frequent coverage at higher resolution (e.g., Quickbird, RapidEye). High resolution data are also useful for early detection of forest cover change and validation of results. The high cost of data and narrow coverage is limiting however [37].

<u>National operational programs</u>

National operational programs utilising GFOI core (Landsat, CBERS-2) and non-core (IRS, MODIS) optical remote sensing data for forest/non-forest cover change monitoring exist in Brazil (PRODES), Australia (NCAS) and India (National Forest Cover Mapping).

- o Amazon Monitoring Program, INPE: A world-leading example of operational, regional monitoring of tropical forests. Segmentation and unsupervised classification of time-series Landsat, DMC and CBERS-2 imagery to estimate annual deforestation rates (Figure 7; [38]). MMU of 6.25 ha applied. The approach could be improved by including degraded forest classes, explicit quantification of accuracy, better delineation of forest/non-forest boundaries, and future integration of SAR (cloud and smoke-penetrating) and CBERS-4 (high resolution and frequent coverage) data. INPE developed the open source TerraAmazon software for manipulation of multi-scale satellite data for deforestation monitoring.

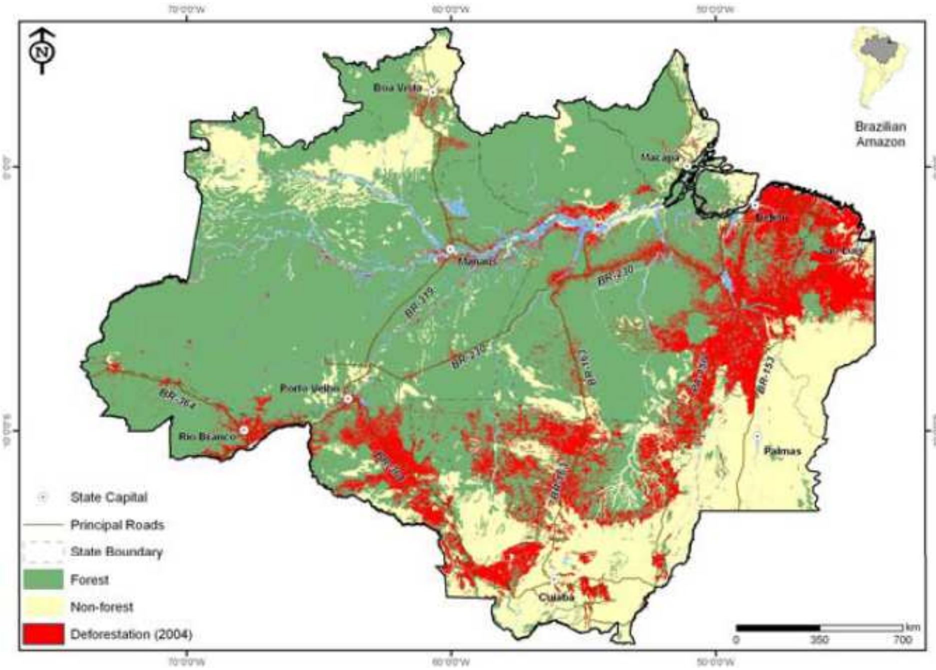


Figure 7 Deforestation map for the Brazilian Amazon, 2004, based on PRODES mapping methodology [38].

- o PANAMAZONIA: National scale mapping of South America's rainforest using fraction images derived from orthorectified Geocover mosaics (1999-2000; http://www.dsr.inpe.br/panamazon/pana_metodo.html). MODIS data subsequently used for annual deforestation monitoring (from 2005).
- o Australia's NCAS: Annual forest updates produced by refinement of single-date, Landsat derived forest cover probability images using a Bayesian conditional probability network (CPN) that detects and resolves false change [6].
- o NCAS National Forest Trend (NFT) information: Produced from a Landsat-based vegetation cover index that is sensitive to changes in forest density [39]. NF is not currently used in carbon accounting, but provides detailed information on forest cover dynamics suitable for informing on environmental change.
- o National Forest Cover Mapping, India: Forest cover change is assessed on a 2-year interval using Landsat MSS/TM imagery and IRS-1B/1C/1D/P6 LISS-II/III data [30].

<u>Sub-national demonstrations</u>

Sub-national demonstrations have informed on deforestation rates and the fate of deforested and afforested land. Mapping approaches have utilised both GFOI core (e.g., Landsat) and non-core (e.g., MODIS, RapidEye and SPOT) data streams.

- o Colombia: Forest cover change map produced using Landsat TM/ETM+ data (2005 – 2010; [18]).
- o EC JRC TREES-3 project: Tree cover change in the tropics and Europe monitored over three time periods (1990-2000-2005) by visual assessment of Landsat data (Figure 8; [40]). Forest change areas are described by experts with extensive regional knowledge (e.g., the change process, type of forest affected, speed and time scale of change and main drivers of change, are described for each area).

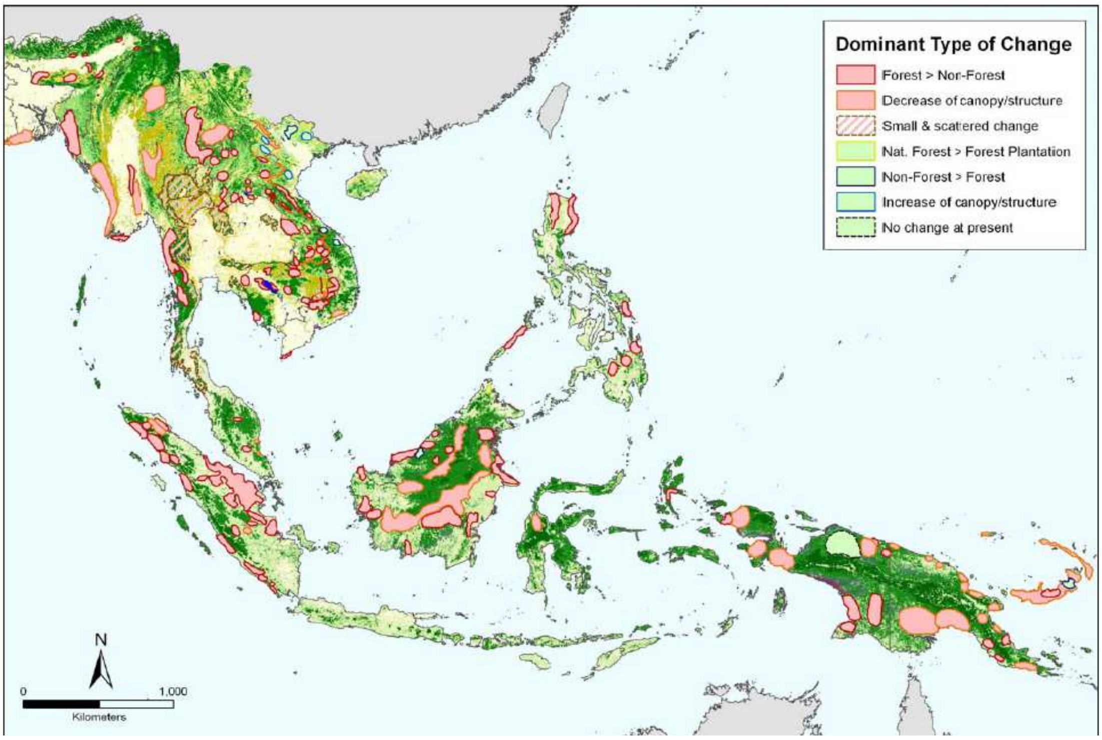


Figure 8 Regional pattern of forest cover change in SE Asia, interpreted from Landsat imagery [40].

- QLD SLATS program: Image transforms and a non-parametric classifier are applied to time-series Landsat TM and ETM+ data, and combined in a model to determine the probability of woody vegetation change >1 ha [104]. Continuity of available optical satellite imagery is paramount to future SLATS reporting. Partial failure of the ETM+ instrument on Landsat-7 in 2003 resulted in large areas of missing data, and problems with Landsat-5 led to reduced coverage over Queensland during drier months. The transferability of SLATS methodology to the newly launched Landsat-8 will require investigation.

<u>Promising R&D case studies</u>

Few R&D studies have investigated the use of multi-resolution optical data for quantification of forest/non-forest cover change.

- Colombia: RapidEye (5 m) data used to map forest cover change over 2009-2011 [41]. Product yet to be validated.
- Cameroon and Central African Republic (CAR): The European Union Framework Programme 7 (EU FP7) Collaborative Research Project Reducing Emissions from Deforestation and Degradation in Africa (REDDAF) aims to develop improved EO based methods for forest cover change mapping (http://www.reddaf.info/content/service-development-and-integration). Forest cover maps for 1990, 2000 and 2010 were generated using Landsat and RapidEye data for Cameroon and CAR. Forest cover change was mapped between 1990 – 2000 and 2000 – 2010 using the forest cover maps and additional EO data such as DEIMOS.
- Democratic Republic of the Congo: ESA GMES Service Element on Forest Monitoring (GSE FM) REDD Pilot Project in the DRC (http://www.redd-services.info/content/gse-fm-redd). Production is underway for national forest cover maps (1990, 2000, 2010)

and forest cover change maps using a combination of optical EO data (e.g., Landsat, DMC, RapidEye, SPOT). Methodology development for validation is on-going.

- o Republic of Gabon: ESA GMES Service Element on Forest Monitoring (GSE FM) REDD Pilot Project in the Republic of Gabon (http://www.redd-services.info/content/gse-fm-redd). Production is underway for national forest cover maps for 1990 using Landsat TM, 2000 using Landsat ETM+ and 2010 using a combination of Landsat ETM+ and Terra ASTER data [195]. Ancillary data, including the interactive forest atlas of Gabon, SRTM DTM and field data are used in the classification process. National forest cover change will be mapped for the periods 1990 – 2000 and 2000 – 2010. Methodology development for validation is on-going.
- o Sumatera and Kalimantan: Forest cover loss (2000-2008) mapped using Landsat ETM+ and MODIS data [45]. The integration of the spatial detail of Landsat and temporal frequency of MODIS presented a viable solution to detection of change in an area where cloud-free images are difficult to obtain. The use of multi-year per-pixel trajectories for estimation of spatially explicit forest cover loss was advocated.
- o A fully automated software toolkit, CLASlite, was developed to work with Landsat, SPOT and other satellite sensor data, for mapping forest cover, deforestation and forest disturbance [106]. The software comprises advanced atmospheric correction, spectral signal processing and classification routines. Application of the software was successful in Brazil and Peru deforestation and degradation scenarios. The software is suitable for use by non-experts and contributes to REDD and conservation and management efforts that promote sustainability of ecosystems.

Radar capabilities

SAR is a useful complement to optical remote sensing for forest monitoring in tropical regions affected by cloud cover and inclement weather. The extent of time-series of not as extensive as for optical systems, but there is sufficient data to generate a recent baseline of forest cover against which to assess change [16]; [51]; [48]. JAXA's ALOS PALSAR satellite has, since late 2006, provided a dedicated stream of L-band data to support regional to global forest cover monitoring [133]; [134]. The loss of PALSAR in May 2011, lack of an alternative L-band data source and lack of coordinated data supply from other SAR satellite providers, has hampered the operational development of SAR.

There are no existing operational radar-based national forest monitoring programs, however, the potential to extract forest cover and trend information from SAR provides new opportunities for supporting national forest inventory and REDD+ reporting. Agencies such as INPE (Brazil), LAPAN (Indonesia) and countries including Mexico, Colombia and Cameroon have begun investigating radar based methods for forest monitoring and biomass assessment [46]; [47]; [18]; [42]. Several promising R&D case studies demonstrate the potential application of multi-frequency SAR for forest/non-forest cover change monitoring.

L-band SAR data can be used stand-alone. Time-series data is required, with semi-annual or better coverage. Dual polarisation is a requirement. C-band SAR can be used under an existing forest mask derived from other satellite data (i.e., Forest/Non-Forest Cover product). Dense time-series (e.g., monthly) coverage is required.

<u>Sub-national demonstrations</u>

- o Xingu Basin, Brazil: Decadal deforestation monitoring using JERS-1 (1996) and PALSAR (2007) imagery [105].

<u>Promising R&D case studies</u>

- Sweden: Threshold algorithm applied to time-series PALSAR HV backscatter data (July 2007 – October 2008) to detect clear cuts [48]. There was good contrast and temporal consistency in F/NF signatures in L-band HV data. L-HH backscatter was more affected by environmental conditions. A decline in L-HV backscatter between dates was observed following clearing. Clear-cut detection was accurate to within 5 % of reference data. The algorithm was subsequently applied to PALSAR FBD strip data (50 m resolution) to map clear-cuts for all of Sweden for the period 2008-2010 [161]. Accuracy of 72.5 % (pixels correctly detected in clear-cuts) and 85.9 % (when applying a 1-pixel edge-eroded version).
- Riau, Indonesia: Broad-area deforestation monitoring using time-series ENVISAT ASAR Wide Swath (WS) data [42]. There was improved separation of plantation types and development stages compared to SPOT VGT (Figure 9).
- Riau, Indonesia: Deforestation mapped using time-series ALOS PALSAR ScanSAR data [50]. An automated routine was developed that detects abrupt changes in backscatter caused by deforestation and uses temporal analysis to locate the timing of the event to within 46 days. Comparable results were obtained using FBD data but the latter required more complex data processing.
- Central Kalimantan, Indonesia: Forest cover change in peatlands assessed using ASAR Alternating Polarisation mode (APP) data (2005 – 2007; [42]). A replicable methodology was developed using automated image compositing and classification routines to identify change >0.5 ha in scale.

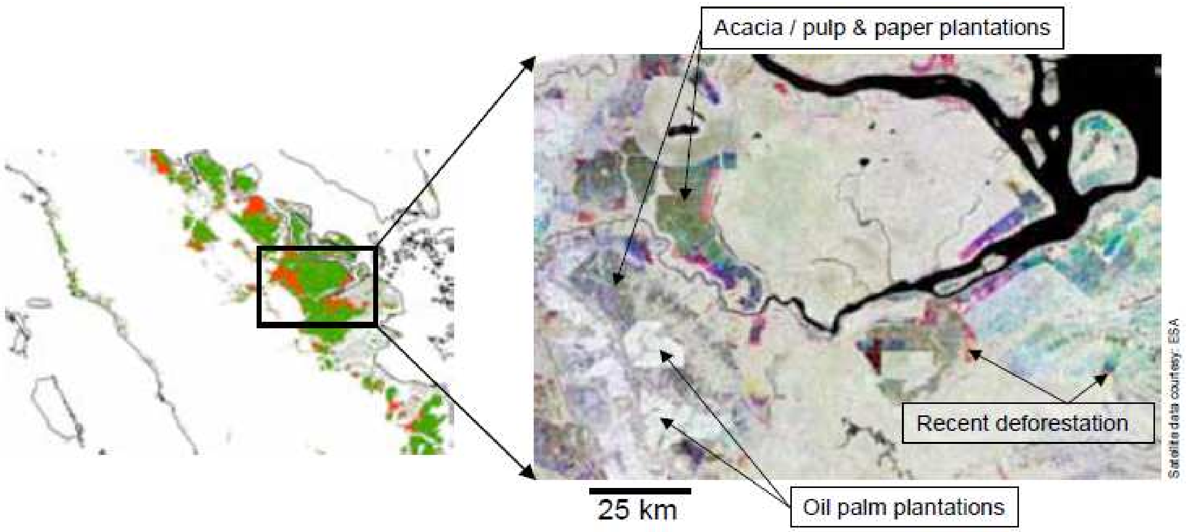


Figure 9 Deforestation arising from plantation development monitored using ENVISAT ASAR wide swath (150 m resolution) data [42].

- Amazon: Deforestation mapped using ENVISAT ASAR Image mode (IMS) acquired in dry season (August, 2004 and 2005; [46]). Wet season images were less useful for detecting change. Single WS images were not reliable for detecting deforestation unless the area was completely cleared. A multi-sensor approach, combining optical, L- and C-band SAR data was recommended for an operational deforestation monitoring system.
- Para state, Brazil: Forest change determined by supervised Wishart classification of polarimetric RADARSAT-2 data (September 2008 and October 2009; [47]). Classification accuracy was 71 % for 2008 and 89 % in 2009. Precipitation a few days prior to image acquisition affected the discrimination of classes. Consequently, change estimates differed by a factor of 5.

Interoperable capabilities

The integration of multi-sensor data, including optical systems with different spectral, spatial and temporal resolutions, and also radar, can assist in resolving ambiguities in forest/non-forest cover change information, and fill gaps in, and extend the data record. The combination or fusion of optical and radar has demonstrated some promising results for forest monitoring [49].

Promising R&D case studies

- Tasmania: Joint SAR-optical processing in a Bayesian multi-temporal system [49]. Forest extent maps for 2008 based on SAR-optical (PALSAR-Landsat) and optical-optical (Landsat-only) time-series processing were 95.8 % in agreement.

Annex B.6 Near-Real Time Forest Change Indicators

This product provides early warning indicators of potential changes in forest cover. Low accuracy is sufficient as the product is not intended for quantitative analysis. Low spatial resolution (100 – 250 m) EO data is sufficient (e.g., MODIS, PALSAR ScanSAR). High temporal observation frequency, monthly or better, is needed for this product. Coarse resolution, frequent measurement can be used as a first alert to disturbance, with targeted high resolution acquisition thereafter. All optical sensor data is potentially useful. L-band ScanSAR and single polarisation data are potentially useful. Dual polarisation L-band SAR is preferable. C-band SAR can be used stand-alone under an existing forest mask derived from other satellite data (i.e., Forest/Non-Forest Cover product). Dense time-series data is required.

Optical capabilities

National operational examples

- INPE, Brazil: The Real Time Deforestation Detection System (DETER) is a prime example of a national operational system for near-real time (NRT) forest change detection. DETER identifies the approximate location and extent of new occurrences of change in the forest each month at 250 m resolution (http://www.obt.inpe.br/deter/). Monitoring capability is afforded through the use of satellites with high frequency coverage at coarse resolution, including MODIS Aqua and CBERS-2. The coarse resolution and cloud cover is limiting to detection of change however. The system was designed for rapid warning and to support surveillance of land clearing. Higher resolution Landsat and IRS imagery has been used to validate DETER deforestation data.
- Daily global MODIS products have been used in early warning systems implemented by, for example, the USDA-FS National Forest Threat Early Warning System [186], Geoscience Australia's Sentinel national bushfire monitoring system (http://sentinel.ga.gov.au/acres/sentinel/index.shtml), and the Global Fire Monitoring Centre (http://www.fire.uni-freiburg.de/), for detection and monitoring of active fires. The daily temporal resolution and multispectral capabilities of MODIS have been exploited to develop several global fire-related multi-annual products [54]. The coarse resolution is limiting, but provides extensive coverage, and demonstrates potential for integration with higher resolution data for mapping burned areas at the required resolution. Medium resolution optical data (e.g., Landsat) could be used to assess longer term fire history and provide quantitative information on vegetation type and condition. The link with estimation of carbon emissions requires further research.

Sub-national demonstrations

There is limited R&D in the development of NRT systems for forest change, and as such, there are only few sub-national demonstrations and promising case studies.

- The Continuous Monitoring of Forest Disturbance Algorithm (CMFDA): Developed using a hyper-temporal Landsat-7 dataset collected over 2 years [55]. Disturbance pixels are identified when change is observed at least three times in consecutive images. Accuracies >94 % were achieved in Savannah River Basin, SE USA. Method shows potential to form part of an operational early warning system for forest cover change.

Promising R&D case studies

- NOAA: Global, real-time, weekly AVHRR derived green vegetation fraction (GVF) images are used for operational weather prediction and hydrological modelling [56]. The algorithm may be useful for NRT forest disturbance detection [37].

Radar capabilities

Sub-national demonstrations

- INPE, Brazil: ALOS PALSAR ScanSAR images were used to detect deforestation polygons complementary to those identified in the optical DETER system [58]. Around 50 % of deforestation polygons could be identified using images without orthorectification or radiometric correction applied. Polygons located in flat terrain were easier to detect than those in steep terrain. The size and shape of polygons affected detection. The idea was to operationalise the use of radar in DETER to prepare for future integration of Brazilian MAPSAR and CBERS-2 satellite data.
- IBAMA, Brazil: The only example of a pre-operational SAR based system for deforestation monitoring and law enforcement in the field [57]. PALSAR ScanSAR data were delivered to IBAMA in near-real time by JAXA. The wide acquisition mode provided repeat observations that complemented the short response time of the optical monitoring system, particularly when cloud cover was limiting. Multi-temporal colour composites were used to detect new areas of deforestation in the Amazon. Prior to the failure of ALOS, IBAMA had intended to implement the program (called 'INDICAR') in an operational manner. For maximum effectiveness, the use of a combined satellite optical and SAR system was recommended.

Promising R&D case studies

One R&D case study demonstrated all-weather hot-spot monitoring using high resolution radar data.

- REDD Fast Logging Assessment and Monitoring Environment (REDD-FLAME): a high-resolution add-on for an existing, semi-operational forest monitoring system, providing hot-spot monitoring for areas at risk of deforestation (http://redd-flame.info/; [199]). The system focuses on early detection of logging activities using (primarily) high resolution SAR data (e.g., TerraSAR-X. RADARSAT-2), but also optical (e.g., RapidEye and future Sentinel-2) data. An example of a forest cover change map generated using time-series TerraSAR-X data, and a burned area map generated using RapidEye data acquired over Mozambique is shown in Figure 10. The collaborative environment under which REDD-FLAME was developed, with test sites in Indonesia, Brazil and Mozambique, and covering a range of forest types and deforestation issues, lends itself to the versatility of the system for tropical and sub-tropical forest monitoring, carbon accounting and resource management. Algorithm improvement is targeting radar speckle reduction and seasonal effects (primarily in optical data) for increased detection sensitivity [200].

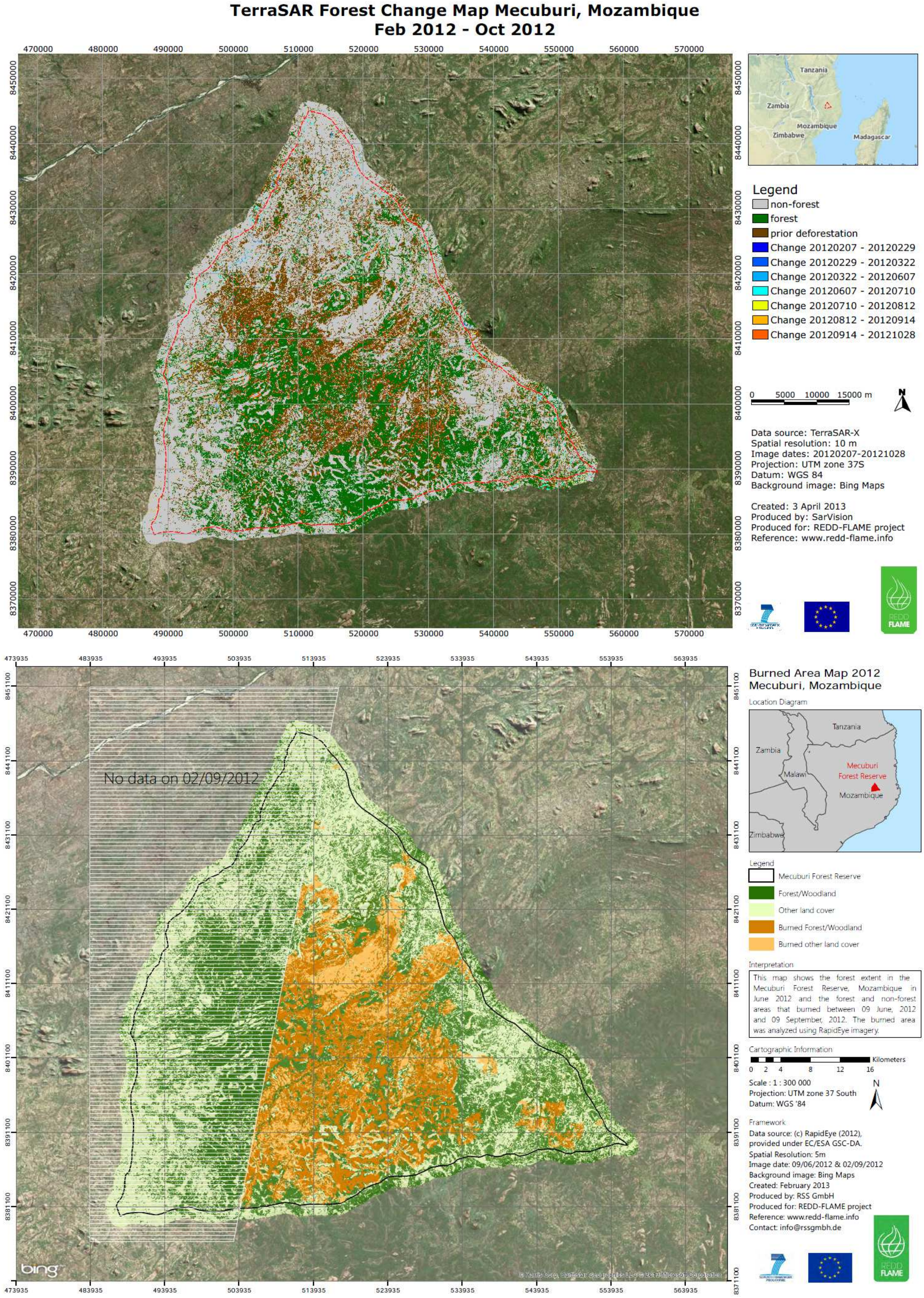


Figure 10 Forest change map generated from time-series TerraSAR-X data (top), and burned area map generated from RapidEye data (bottom) for Mozambique [http://redd-flame.info/].

Annex B.7 Evaluation of operational status: Forest Area and Change

Table B.3 Evaluation of operational readiness of GFOI Forest Area and Change information products.

Code	National operational examples	Sub-national demonstrations	Promising R&D case studies	EO data availability	Additional R&D needs	GOFC-GOLD Reference
Forest / Non-Forest	-NCAS, Australia	-Xingu, Brazil -QLD SLATS -Boreal (European Russia)	- EU ReCover	Core: Landsat-5 Landsat-7	-Cloud-filling using multi-scale optical - Integration of alternative (high res) and future optical -Integration of optical and C-band SAR -Benefits of C- and X-band SAR	- Use Landsat-type RS data - Historical REF scenario: 1990, 2000, 2005, 2010 - MMU 1-6 ha - Geo-location accuracy <1 pixel - Consistent methods at repeated intervals - Consider inter-annual variability in image selection - Augment cloudy images with coarse resol. optical - Potential of radar pending acquisition, access & methods - High resol. for cal/val - Relating deforestation to emissions estimation, carbon transfers between pools
	-NFI, India	-EC JRC pan-Euro forest -WFW Euro forest map -GEO Mexico -GEO Xingu -GEO Tasmania	- GEO Tasmania - EU ReCover - Laos [221]	Non-core: IRS LISS AVHRR RapidEye Quickbird Kompsat-2 ALOS PALSAR ALOS AVNIR-2 RADARSAT-2 ENVISAT ASAR		
Forest/Non-forest Change	-INPE PRODES -NCAS NFT, Australia -India [30]	-GEO Colombia -EC JRC, TREES-3, SE Asia -QLD SLATS	-Indonesia proj -Cameroon - Central African Republic -D.R Congo - Republic of Gabon	Core: Landsat-5 Landsat-7 CBERS-2	-Burned area mapping methods -Cloud-filling using multi-scale optical -Multi-year pixel trajectories -Pixel mining -SAR-optical integration and fusion - Use of dense time-series C-band SAR	
	-India [30]	-Xingu, Brazil	-Colombia -Cameroon - Central African Republic -D.R Congo - Republic of Gabon -CLASlite software -Sweden proj -Indonesia proj -Amazon proj -GEO Tasmania	Non-core: IRS P6 LISS-II/III RapidEye SPOT DMC Terra ASTER JERS-1 ALOS PALSAR ENVISAT		
Near-Real Time Forest Change Indicators	-INPE DETER	-CMFDA, USA		Core: CBERS-2 Landsat-7	-Cloud-filling - Hyper-temporal processing methods -Spectral indices -Other data sources (Sentinel, ScanSAR) -Validation of products	- Coarse resol. for identifying rapid change
	-INPE DETER	- INPE, Brazil - INDICAR, Brazil	-GVPS, USA -REDD-FLAME	Non-core: MODIS IRS AVHRR ALOS ScanSAR RapidEye TerraSAR-X RADARSAT-2		

Annex B.8 Forest stratification map

This product is a map showing relevant forest types. Forest classes to be included vary between countries and eco regions, including when applicable, regionally significant types such as e.g. peat swamp forest, mangrove, low density forest, and secondary/regrowth. Distinction is required between natural forest and plantations. The suggested stratification is Primary Forest (PF), Modified Natural Forest (MNF) and Planted Forest (PF), in accordance with the FAO Forest Resources Assessment [212].

Forest type maps are useful for stratification and biomass estimation, forest planning and biodiversity monitoring [37]. For each forest type, information is required about its estimated carbon content per unit area (the difference in carbon densities being a carbon emission factor), its size and, in the case of the spatially explicit Approach 3, its geographical location.

The need for improved distinction of forest types that can be associated with different emission factors (differences in carbon contents) has been highlighted as being of key importance to accommodate REDD reporting [2]; [3]. If degraded forest is regarded as a different forest type, degradation can be handled in this way.

Optical capabilities

The differentiation of different forest types and their condition is more technically challenging than simple presence/absence of forest. Often a combination of photo interpretation and digital image classification techniques is used. Optical data can be used stand-alone if cloud-free coverage is obtained. The inclusion of the SWIR band improves class distinction. Texture measures may also help discriminate certain forest types (e.g., regular row spacing in plantations; [37]). At least one annual national coverage is required, although dual-season coverage is preferred. A dense time-series may improve discrimination due to seasonal dynamics and plantation cycles [135]; [131]. High resolution imagery is useful for training and validation of algorithms. Coarser resolution data is useful for identifying large-scale forest trends. Data acquired by future hyperspectral satellites (e.g., EnMAP) are anticipated to improve mapping of diverse forest types.

National operational examples

- Copernicus Land Monitoring Services: pan-European High Resolution Layers (HRL) including forest type (http://land.copernicus.eu/pan-european/high-resolution-layers/forests/view). 20 m resolution products include the dominant leaf type (MMU 0.5 ha, threshold of 10 % tree cover density), and trees under agricultural use and urban.

Sub-national demonstrations

Sub-national demonstrations of forest type mapping utilising GFOI core (e.g., Landsat) and non-core (e.g., AVHRR, SPOT, MERIS) data streams are available.

- Europe: EC JRC produced the first high resolution forest type map of Europe. Segmentation, clustering and nearest neighbour classification of Landsat ETM+ data for 2006 [59]. Accuracy > 80 %.
- Continental SE Asia: EC JRC classified forest types using dry season SPOT-4 VGT images (Figure 11; [62]). Accuracy of 92 % compared to interpretation of Landsat TM. The coarse spatial and spectral resolution was limiting to detection of fragmented forest and gradual transitions between forests and regrowth or shrub classes.
- Tropical South America: EC JRC classified forest extent using AVHRR data (http://bioval.jrc.ec.europa.eu/products/veget_map_tropical-sam/southamerica.php).

The coarse resolution was limiting to discrimination of gradual interface formations, including humid and seasonal forest types.

- NSW, Australia: Combination of object-oriented, unsupervised classification of time-series SPOT-5 data and species distribution modelling to map regional vegetation types [64]. Validation by interpretation of high resolution ADS40/80. The high spatial resolution facilitates mapping of individual trees and assessment of clearing.
- Victoria, Australia: Ecological Vegetation Class (EVC) mapping using a model approach and time-series Landsat data [60].
- Trinidad and Tobago: Tropical forest types mapping using multi-season Landsat and multi-season high resolution data [61]. Gap-filled multi-season imagery significantly improved class-specific accuracy. Some communities were distinguished using imagery acquired during drought or specific flowering times, or because of unique canopy structure identifiable in high resolution imagery.
- Congo Basin: 20 land cover classes, including forest types, mapped using 19 months of ENVISAT MERIS and 8 years of daily SPOT VGT data [63]. Overall accuracy of 71.5 %.

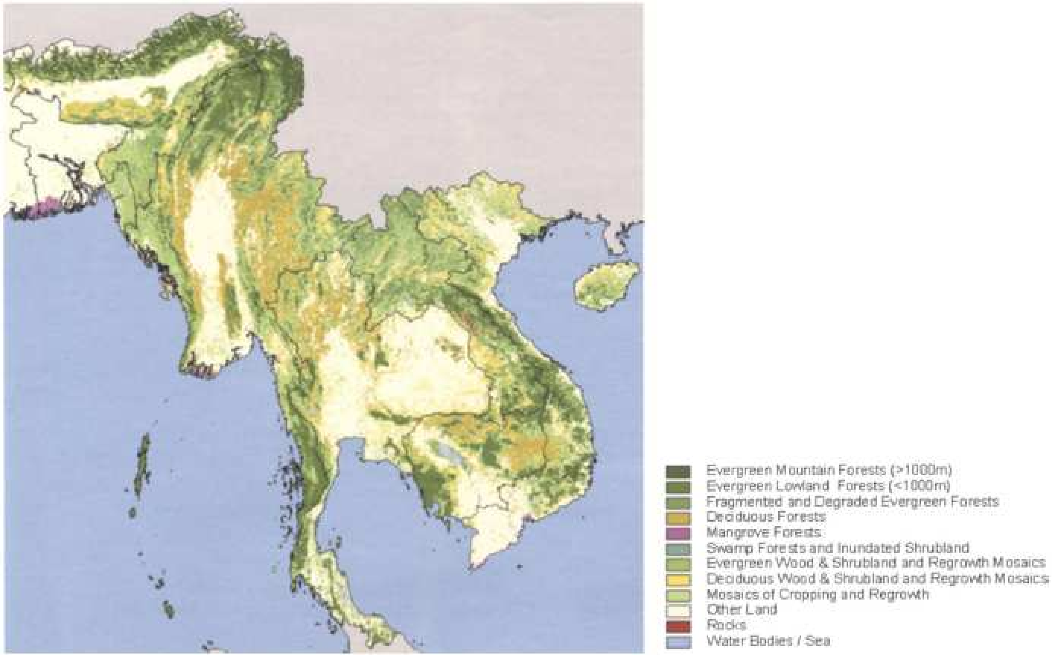


Figure 11 Forest cover map of continental SE Asia generated using SPOT-4 VEGETATION satellite imagery [62].

<u>Promising R&D case studies</u>

- Northern Greece: Multi-scale, object based, decision classification of high resolution Quickbird data to map forest types [65]. Overall accuracy of 80 %. Inclusion of texture images improved the result.

Radar capabilities

Radar has not been used for operational forest type mapping, but a number of promising R&D case studies may see its inclusion in future integrated optical-radar programs. L-band SAR can be used if dual polarisation is obtained. Dual-season coverage and combination with optical data is preferred. C-band SAR is generally insufficient on its own, although a dense time-series may improve the discrimination of forest types [211]. Ideally, higher frequency SAR data should be used in combination with L-band or optical data. Dual polarisation is required. Structural characterisation using LiDAR and InSAR may also assist in forest type mapping [136]; [137].

Promising R&D case studies

- Iwokrama, north Rupununi, Guyana: Forest type map produced using ALOS PALSAR data [41]. L-band penetration and sensitivity to biomass assisted in the discrimination of forest, swamp forest, woodland and shrub communities, as well as flooded and non-flooded areas.
- Mawas, Indonesia: Combination of RADARSAT-2 Wide Beam (WB) and ALOS PALSAR FBD improved the contrast between forest types (e.g., peat and heath forest) and within forest (biomass) variation [52].
- Sarawak, Borneo: RADARSAT-2 WB and ALOS PALAR FBD improved the contrast between forest and acacia plantation [52].
- Riau Province, Indonesia: Classification and monitoring the dynamics of tropical plantations using time-series ENVISAT ASAR data [211]. Both VV and VH were significant for discriminating different forest types. The underlying soil type (peat or non-peat) in acacia plantations had significant impact on the backscatter and classification results. Overall classification accuracy of 86.2 %. Comparative studies with L-band ALOS PALSAR data revealed the highest information content in the cross-polarisation (HV) channel. The study suggested that future acquisitions by Sentinel-1 could support tracking of plantation status and monitoring the activity of pulp companies.
- Minnesota, USA: Moderate success using RADARSAT-1 for discriminating forest types [70]. Separability of 11 forest types increased following speckle filtering and inclusion of first-order texture derivatives.

Interoperable capabilities

Classification accuracy typically decreases with an increasing number of forest classes. The integration of radar and optical or other data types may improve the accuracy of forest type classifications. The inclusion of DEM height can also improve the separation of forest types.

Promising R&D case studies

- Rondônia, Brazil: Decision tree classification of time-series Landsat MSS (1975-2003) and SRTM data to separate lowland forests [68]. Overall classification accuracy of 69 % for 14 classes.
- Costa Rica: Decision tree classification of time-series Landsat TM, SRTM DEM derived and climatic variables [69]. 17 forest classes, including plantation and successional forest, mapped at 93 % accuracy.
- Central India: Fusion of ENVISAT ASAR and IRS-P6 LISS-III for improved forest type discrimination (> 90 %; [66]).
- Northern-Oriente, Ecuador: Integration of RADARSAT, Landsat ETM+ and digital video data to discriminate African oil palm plantation and other forest/land cover types [67]. Fusion of optical reflectance and SAR texture achieved user and producer accuracies of 83 % and 90 %. Further investigation of radar texture metrics and class specific processing strategies was recommended.

Annex B.9 Degradation Type map

Any type of degradation, e.g., selective logging, partial fire damage, pests/diseases, drought and fuel-wood collection, or proxies or indicators such as logging roads, vegetation index changes, changes in canopy structure, proximity to agricultural activity or infrastructure, should be taken into consideration and mapped if feasible.

Optical capabilities

National operational examples

- DEGRAD, INPE: Presents the only current example of a national operational system for forest degradation monitoring (http://www.obt.inpe.br/degrad/). Only areas of deforestation where the entire forest area is not removed are mapped. Detailed mapping of forest areas where conversion to close cut is likely is undertaken by photo interpretation of contrast enhanced Landsat and CBERS-2 imagery (2007 – 2010). Mild to heavily degraded forest with a MMU of 6.25 ha is mapped on an annual basis.

Promising R&D case studies

There are no large-scale demonstrations of degradation type mapping, but a few promising R&D case studies demonstrate potential for retrieving information on changing land use patterns and identifying selective logging using GFOI core (e.g., Landsat) and non-core (e.g., IKONOS, SPOT-4 and TerraSAR-X) data streams.

- Manaus, Brazil: Time-series classifications of Landsat TM data over 1973 to 2003 provide spatial information on forest age and history of land use prior to abandonment to regenerating forest (Figure 12). The 30 m resolution data is sufficient for informing on changes in species dominance following clearing and re-clearing events (Source: R.M. Lucas, University of Wales).

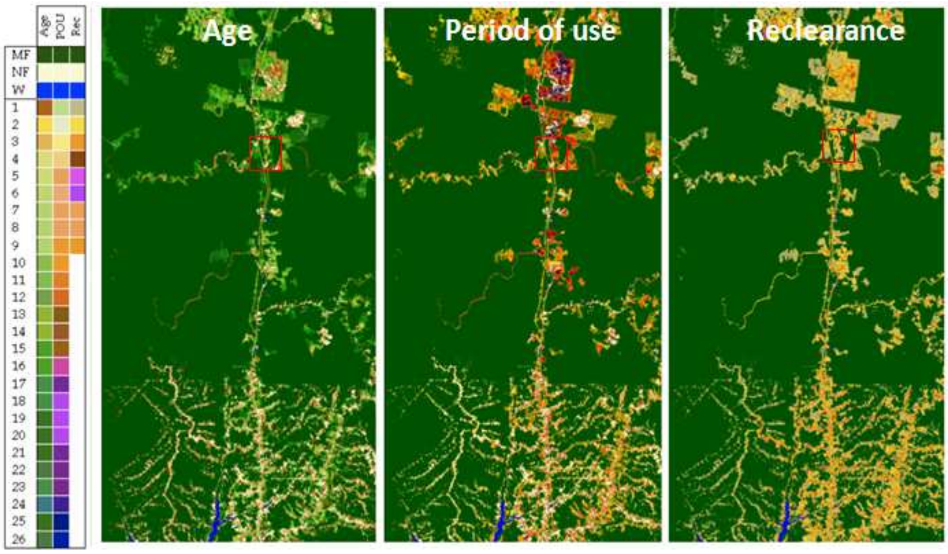


Figure 12 Spatial information on forest age and history of land use in Manaus, Brazil, derived from time-series classification of Landsat data (Source: R.M. Lucas, University of Wales).

- Eastern Amazon: Decision tree classifier used to define a rule set for separating forest classes using SPOT-4 derived fraction images (including vegetation, non-photosynthetic vegetation, NPV, soil and shade; [79]). The spatial extent of degraded forest, logged forest, forest regeneration and intact forest was mapped in the process (Figure 13). Good agreement (86 %) with IKONOS imagery, and high correlation (r2 = 0.97) between total live AGB of degraded forest classes and Non-Photosynthetic Vegetation (NPV) fraction image.

- Cameroon and Central African Republic (CAR): The European Union Framework Programme 7 (EU FP7) Collaborative Research Project Reducing Emissions from Deforestation and Degradation in Africa (REDDAF) aims to develop EO based methods for mapping the extent of degraded areas and the degree of degradation (http://www.reddaf.info/content/research). An approach based on spectral mixture analysis (SMA) utilising multi-temporal regeneration signals has been developed for forest degradation mapping caused by selective logging. The method overcomes the need for optical data shortly after the occurrence of logging, which is often restricted by cloud cover.

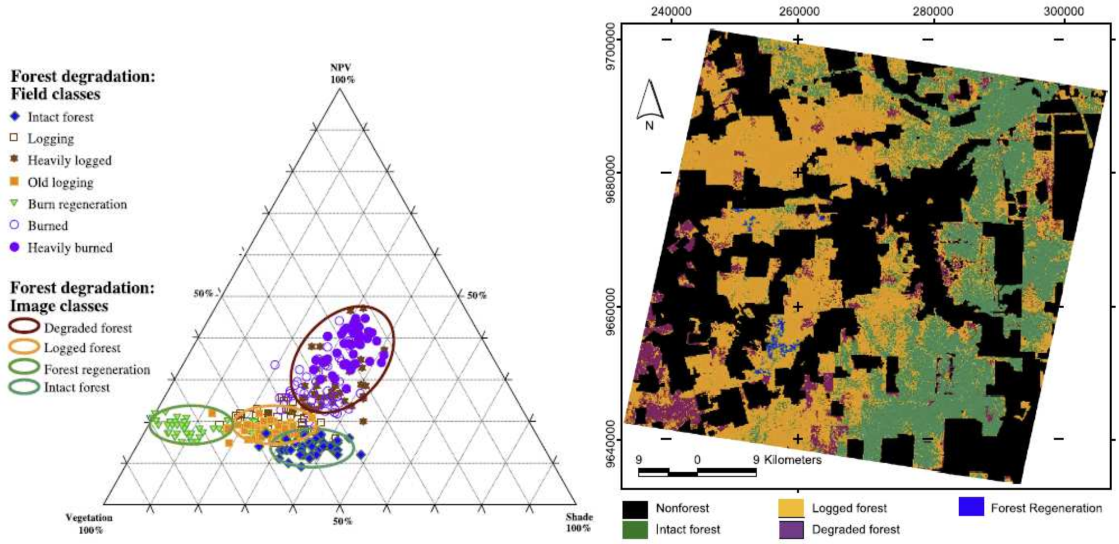


Figure 13 Identification of forest degradation classes using SPOT-4 derived fraction images (left), and forest degradation map derived from SPOT-4 and IKONOS imagery using a decision tree classifier (right; [79]).

Radar capabilities

Promising R&D case studies

R&D studies using VHR SAR, such as that acquired by TerraSAR-X spotlight mode (1 m) and COSMO-SkyMed spotlight and stripmap modes (1 m and 3 - 5 m), and medium resolution SAR, such as ALOS PALSAR, demonstrate the capacity for reliable detection of degradation resulting from complete or partial removal of tree cover, and in areas where optical image availability is limited by near-permanent cloud cover.

- West Colombia: Removal of individual trees detected using multi-temporal TerraSAR-X spotlight data [80].
- Panama: Automated change analysis applied to calibrated TerraSAR-X spotlight time-series to monitor the progress of logging activities (Figure 14; [81]). The high geometric accuracy, high spatial resolution and flexible tasking capability of TerraSAR-X renders it an efficient tool for monitoring permanent sample plots and hotspot areas, including illegal logging activity, where degradation and deforestation occur over rapid timescales [80].
- Cameroon and Central African Republic (CAR): 3D mapping of the forest canopy to detect degradation has been investigated under the EU FP7 REDDAF program (http://www.reddaf.info/content/research). Methods employing InSAR, radargrammetry, and extraction of degradation areas from digital surface models (DSM) have been applied to data acquired by the COSMO-SkyMed X-band SAR in order to detect gaps in the forest canopy due to logging. Difference models generated

from COSMO-SkyMed and SRTM data clearly show gaps and roads as features of degradation.

- Democratic Republic of Congo: Mapping of forest degradation by selective logging using ALOS PALSAR Fine Beam Dual polarisation (FBD), ENVISAT ASAR and TerraSAR-X spotlight data [203]. Multi-temporal change detection was applied to segmented backscatter data, and validated against optical VHR data. The results showed high PALSAR user accuracy (95 %), however the area of selectively logged forest was under-estimated by 37.5 %. The overall accuracy was 70.4 %. PALSAR data demonstrated a high capacity to map newly constructed forest roads. TerraSAR-X user accuracy approached 100 %, but the overall accuracy was 53.6 %. Poor detection accuracy was observed using the ENVISAT ASAR data.

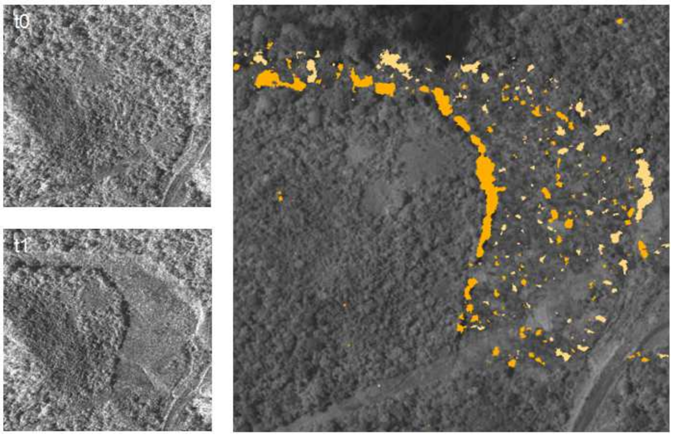


Figure 14 Monitoring clear-cut activities in Panama using TerraSAR-X Spotlight data: (Left) Original TerraSAR-X images from two time periods, (Right) Change indicator map showing the progress of tree felling activities [81].

LiDAR capabilities

To the very best of our knowledge, there is currently limited experience with use of LiDAR for classifying and estimating the extent of degradation in the tropics. LiDAR depicts the 3D distribution of biological material in the tree canopies, and is highly sensitive even to sub-canopy changes. It is therefore expected that LiDAR can be useful for classifying degradation also in tropical forests.

Promising R&D case studies

To the best of our knowledge, only one study has been conducted in which degradation was classified and distinguished from other changes on the basis of LiDAR data [78].

- Boreal forest, south eastern Norway: model-based AGB estimation using field sample plots and LiDAR data available for two dates over an 11 year period [78]. A multinomial logistic regression model was used to predict the change category (e.g., deforestation, degradation or untouched) for every LiDAR cell. Areal change was estimated using field samples and LiDAR data and model-assisted estimators. The change categories were used as post-strata in estimating the net change in biomass. Standard errors of the biomass change estimates were reduced by 18 - 84 % when using LiDAR in the model-assisted approach. Compared to other remote sensing techniques, LiDAR demonstrates high potential to distinguish between activity-based change categories and identifying partial loss of biomass (degradation). Future research should focus on stratification schemes for improved precision of change estimations using LiDAR as auxiliary information.

Annex B.10 Degradation and/or Enhancement of Carbon Stocks

Identification and mapping of degradation is of high priority even if high accuracy cannot be achieved, because of the risk that actions to reduce deforestation could inadvertently increase degradation. This is a significant issue in the negotiations. There is no clear definition of degradation, but it is generally accepted to include any direct, anthropogenic-induced and persistent loss in carbon density over time, but still maintaining sufficient canopy cover to meet the threshold for definition of forest and with no change in land use. The Degradation and/or Enhancement of Carbon Stocks product should also comprise enhancement of carbon stocks, including forest management, natural causes and regrowth. Local forest inventory may present the best approach to detection of subtle change incurred through wood extraction [138].

It is suggested that the following sub-categories, independent of the data used and source of the degradation, be used:

- Qualitative percentage change from a reference condition as estimated for a country or region. The reference condition can be biomass/carbon density, canopy cover or some other vegetation metric.
- Quantitative estimation (e.g., in Mg ha^{-1}) of biomass/carbon density gain/loss (after calibration against ground biomass/carbon estimates).

Optical capabilities

The lack of a standard definition of degradation has impeded the development of operational monitoring systems. There are successful demonstrations at sub-national and local scales however. VHR (e.g., RapidEye) to medium (e.g., Landsat, SPOT, ASTER) resolution optical data can be used for direct observation of canopy damage, small clearings, other structural changes or changes in forest carbon [139]; [140]; [141]; [142]; [143]. The REDD Sourcebook (http://www.gofcgold.wur.nl/redd/index.php) suggests the use of high and very high resolution (VHR, < 5 m) data as degradation may involve the removal of individual trees (i.e., selective logging). VHR data is only available through commercial missions (e.g., RapidEye, Quickbird). Sentinel-2 will provide the highest resolution of the core missions (10 m), and R&D will be required to assess its potential for degradation mapping.

Sub-national demonstrations

The following are examples of qualitative monitoring of degradation using time-series satellite data.

- Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS), North America: Changes in above ground live biomass associated with disturbance and regrowth are assessed by integrating Landsat reflectance trajectories with plot-level biomass data (Figure 15; http://www.fsl.orst.edu/larse/website/projects.html).
- 'Landtrendr', US: Trajectory segmentation of time-series Landsat data to assess forest dynamics in response to insect outbreak and tree mortality [72]; [73]. The process separates noise from, and simplifies trends in pixels. In so doing, stable and change pixels are identified, and the 'life history' of each pixel captured.

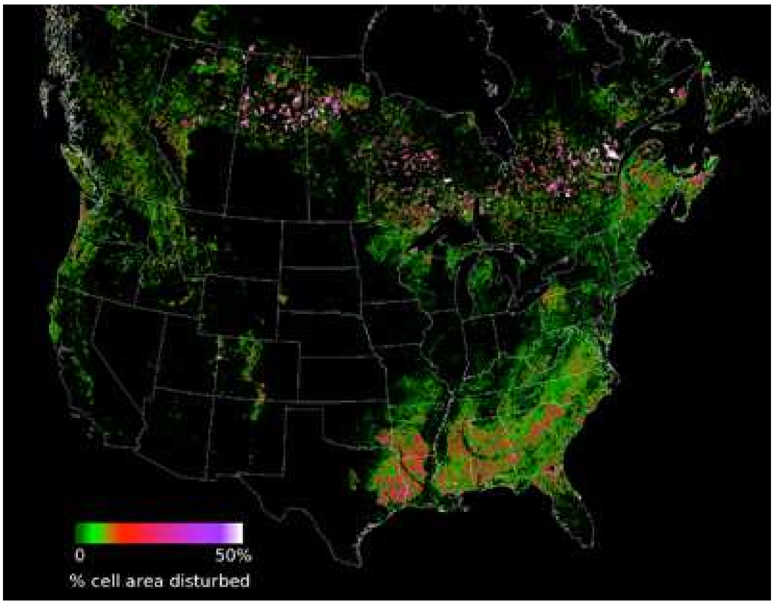


Figure 15 Landsat-derived forest disturbance rate (1990 – 2000), North America (http://ledapsweb.nascom.nasa.gov/).

Promising R&D case studies

Only few R&D studies have demonstrated the potential for thresholding of vegetation metrics to separate degradation and forest classes using time-series multi-resolution optical data (e.g., Landsat, MODIS, Quickbird).

- Mid-Appalachian high region, USA: Defoliation maps produced from unsupervised classification and thresholding of MODIS derived maximum NDVI [74]. High classification agreement (88 %) with Landsat and ASTER data. Daily MODIS 250 m composites outperformed 16-day composites in detecting the extent and location of defoliation patches of 0.25 km2 size.
- Rondônia, Brazil: Humid lowland forest age mapped by applying Threshold Age Mapping Algorithm (TAMA) to time-series Landsat data (1975-2003; [68]). Old growth forest, non-forest and secondary forest classes (in 1-2 year age increments) mapped in the process. User accuracies ranged between 29-87 % (lowland forest age classes) and 93 % (old growth), and producer accuracies between 19-92 % (lowland forest) and 84 % (old growth).
- Gabon and Democratic Republic of Congo: Semi-automated, object-oriented classification of multi-temporal Quickbird images to detect and quantify areas where change has occurred (e.g., forest canopy gaps, small clearings, logging roads) and identify different intensities of degradation [201]. Five levels of forest degradation are defined based on the percentage difference of bare soil between image dates. The study concluded that national estimates of forest degradation could be made in the context of REDD+, and future Sentinel-2 data will likely be of value.
- Kafa zone, south-western Ethiopia: Use of a statistically data-driven method for detecting deforestation and forest degradation using dense time-series Landsat-5 TM and Landsat-7 ETM+ data [202]. The pixel-based Break detection For Additive Seasonal Trends (BFAST) Monitor method models the expected behaviour of a time-series and identifies those pixels that deviate significantly as breakpoints. BFAST Monitor was applied to a time-series of Landsat-derived NDVI images from 1983 - 2011. Pixels that deviated significantly from the stable model were identified as breakpoints, and validated against time-series SPOT-5 imagery. High negative change magnitude breakpoints were associated with deforested areas, and low

magnitude breakpoints were typically associated with forest degradation. Gaps in the time-series and misclassified pixels in the forest reduced the accuracy of the detected breakpoints (and hence forest change). The magnitude of the detected change was related to the type of change, and a threshold was necessarily applied to minimise commission errors. BFAST Monitor provides a useful tool for monitoring deforestation and degradation and frequent time intervals in support of REDD+ MRV systems.

Radar capabilities

There is untapped potential in the use of radar and LiDAR for discriminating degraded forest, both qualitatively and quantitatively. The sensitivity of radar to canopy structure and biomass can be exploited to map changes associated with regrowth or regeneration of natural and planted forest. SAR sensitivity to biomass varies with frequency however. C- and X-band SAR tend to saturate at low biomass levels (25-50 t/ha), L-band saturates at 50-150 t/ha, and P-band saturates around 100-200 t/ha. SAR sensitivity to topography and soil and canopy moisture is also limiting to biomass estimation. Fully polarimetric and interferometric SAR afford more detail on forest structure, and their use may improve biomass estimates [144]. LiDAR signatures can be correlated with disturbance events or used to quantify the area subject to disturbance and the associated loss of carbon [78].

Identification of selective logging, canopy gaps and crown damage requires VHR SAR data; available through commercial missions (e.g., TerraSAR-X/TanDEM-X). LiDAR is also available through commercial operators.

<u>Promising R&D case studies</u>

Only few R&D case studies were found to demonstrate the detection of selective logging and the influence of AGB on reliability of detection using TerraSAR-X data [175], and the potential for degradation monitoring using TanDEM-X data, exploiting the correlation between canopy cover and interferometric coherence [198].

- Northern Brazil: Selective logging detected using TerraSAR-X High Resolution Spotlight (HS; X-VV) data acquired in April 2008 and August 2009 [175]. Object-based change detection was applied to identify target segments with variable spectral and structural properties. The locations of extracted trees were correctly detected with a probability of ~86 %. The influence of tree biomass, crown area and social position/dominance on the reliability of detecting forest degradation was assessed. AGB was estimated for all trees using in situ forest DBH measurements and a general allometric equation. Biomass data were then categorized into five quintiles and producer's accuracy values compared. There was higher reliability of detection of larger trees (quintile 5 - high biomass, 93 % detected) compared to smaller trees (quintile 1 – low biomass, 76 % detected). The study suggested that some region specific adaptations of the method might be necessary, but a semi-automated workflow and consistent results were envisioned.
- Kalimantan, Indonesia: A moderate relationship is observed (r^2 = 0.64) between LiDAR-derived local maxima and interferometric coherence obtained from single-pass TanDEM-X data acquired over peat swamp forest [198]. A canopy height model (CHM) was calculated from the difference of LiDAR-derived digital surface and digital terrain (DSM and DTM) models. Individual tree tops were detecting by applying a local maxima algorithm to the Gaussian-filtered CHM. The local maxima approach to estimating canopy cover is limited where trees are hidden by larger trees or where smaller trees grow close to large trees, and where multiple crowns are associated with a single tree. The results indicated that volume decorrelation, and hence, interferometric coherence, is correlated to forest structure. High canopy cover results in greater volume decorrelation and lower coherence. The capacity for direct or

multiple backscattering processes increases if the crown cover or tree cover density is low. Accordingly, high backscatter and high coherence are observed over open forest. The study concluded that despite the low dynamic range of TanDEM-X coherence data (baseline dependent), information on forest stratification can be retrieved that is of value to global forest monitoring.

Interoperable capabilities

Promising R&D case studies

R&D in Queensland, Australia, is demonstrating high potential to exploit time-series Landsat woody vegetation extent and canopy structural information from SAR for discriminating several stages of regrowth. With systematic data acquisition and dedicated field inventory, an operational framework for monitoring woody vegetation extent and degradation is possible. The examples represent qualitative descriptors of degradation, i.e., regrowth stage, as compared to a reference forest.

- Queensland Australia: Forest areas are discriminated from non-forest by applying a threshold to Landsat-derived Foliage Projected Cover (FPC), which is produced routinely for the State (Statewide Land Cover and Trees Study, SLATS). The separation of woody regrowth following clearing cannot be undertaken with confidence however [53]. Studies using airborne SAR (AIRSAR) data have also shown that woody regrowth cannot be mapped using either C-, L- or P-band SAR data alone. The integration of Landsat-derived FPC and SAR backscatter data is promising however, as regrowth supports high FPC and C-band backscatter and low L- and P-band backscatter. Brigalow-dominated regrowth was mapped using a combination of FPC and AIRSAR L-band data, and showed good correspondence with maps generated using Hymap data. Archive Landsat FPC and JERS-1 data also demonstrated potential to map regrowth, so providing insight into historic vegetation dynamics. Future monitoring potential is high given the on-going and systematic data acquisition afforded by next generation sensors such as PALSAR-2, Sentinel and Landsat-8.
- Brigalow Belt Bioregion (BBB), Queensland Australia: Regrowth classification based on combination of ALOS PALSAR L-band HH and HV backscatter and Landsat derived FPC and thresholds for discriminating non-forest, early-intermediate regrowth and mature forest (Figure 16; [75]).
- Queensland Australia: In a concurrent study, Landsat and PALSAR data were segmented and each object assigned a growth stage by comparing backscatter and FPC to reference distributions (field plots). Overall accuracy was >70 %, increasing to 90 % when intermediate regrowth was excluded [76].
- Queensland Australia: Relationships between Landsat time-series and LiDAR vertical profiles demonstrate potential for forest disturbance monitoring in terms of carbon gain/loss over time [77]. Landsat data acquired since 1970 are used to determine annual rates of change. LiDAR profiles exhibit unique signatures when related to disturbance events (e.g., chaining, stem injection and logging) at discrete times over the Landsat record (Figure 17). With knowledge of land use history and management practices, the combination of datasets presents a unique approach to characterisation of current state and forest disturbance dynamics over time.

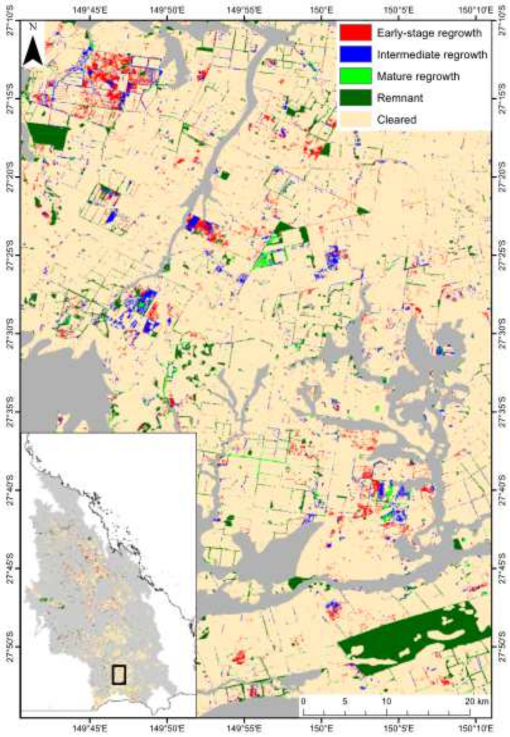


Figure 16 Regrowth classification in the Brigalow Belt Bioregion, Queensland, Australia, using a combination of ALOS PALSAR L-band HH and HV and Landsat derived Foliage Projective Cover (FPC; [75]).

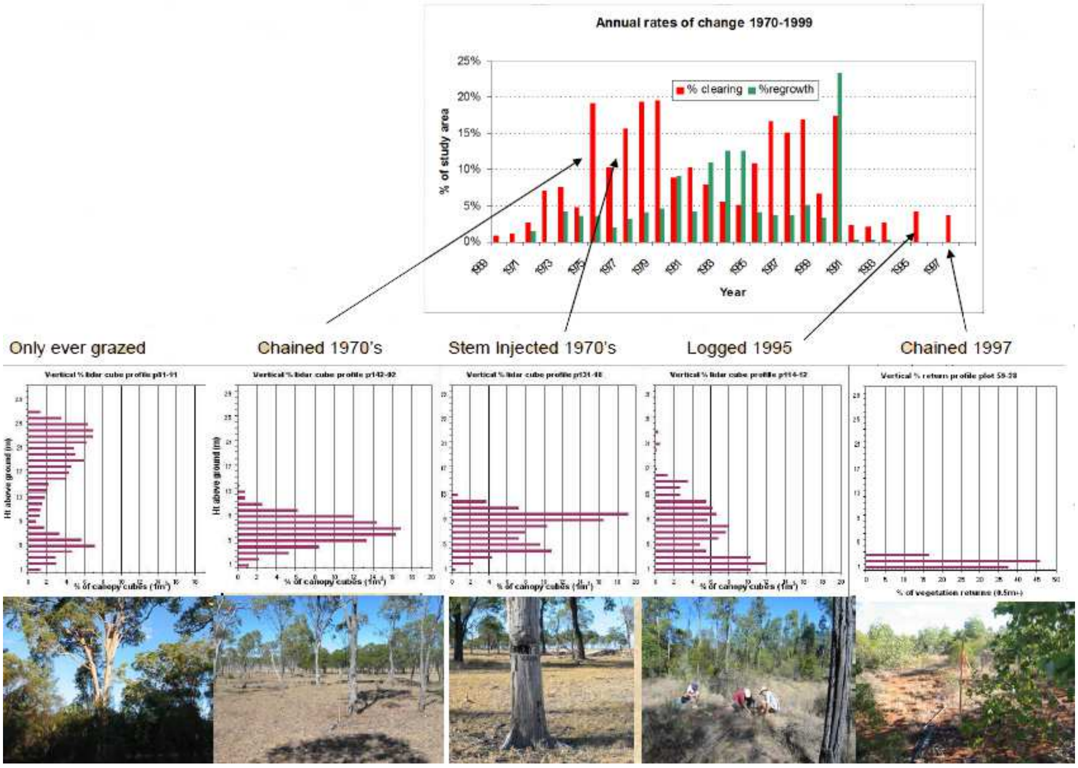


Figure 17 Relationships between Landsat time-series and LiDAR vertical profiles for assessing forest disturbance [77].

Annex B.11 Above-ground Biomass Estimation

Map showing vegetation/land cover stratified into broad above-ground biomass (AGB) categories. It can also be used to derive proxies for emission factors for reporting purposes. The AGB product is distinct from the degradation/enhancement of carbon stock product in that AGB is estimated for cover classes additional to forest.

Above ground biomass (AGB) can be estimated with and without use of remote sensing information. In direct methods, a statistical estimate is obtained using a sample of field plots where the field-based value on each plot is obtained by measurements of the trees and application of an allometric model. When using remote sensing data in the estimation (indirect approach), a model is typically fitted which establishes a relationship between forest structural parameters and biomass on the plots using satellite derived indices or model based approaches [145]; [146]; [147]; [148]; [95]; [100]. Thus, both approaches typically use allometric models for individual species to estimate tree- and plot-level AGB. Satellite-based approaches to AGB estimation would not be possible without appropriate field reference data, either acquired as part of a country's existing NFI or in supplementary field survey.

The remote sensing-assisted estimation can either follow a design-based approach in which unbiased estimators may be used or the estimation may be based on a model-based approach in which it is assumed that the model is correctly specified for the estimator to be nearly unbiased. The first approach assumes that a probability sample of field plots is available, while in the latter approach the availability of a correctly specified model is crucial. The origin of the model is in principle not an issue. Thus, in principle there need not be any local plots available for model calibration, although is generally recommended that the model is constructed from data representing the local conditions in a fairly good way.

Estimation of carbon stocks and change using satellite data is technically challenging. Satellite data that are suited to the task of estimating forest biomass, and hence carbon stock (~50 % of biomass), have only recently become available [149]. Data acquired by penetrative SAR and LiDAR (both airborne and terrestrial) sensors show the most promise for estimation of AGB. Remote sensing data can be used to fill the spatial and temporal gaps in forest inventory data, thereby enhancing estimation of AGB derived from these data [169]. The strong correlation between satellite data and vegetation structural parameters including biomass, and the opportunities for repeat coverage over large areas are favourable for the use of remote sensing data in AGB assessment.

Global estimates of forest carbon stocks are largely derived from forest inventory and are fraught with uncertainty. Wall-to-wall, pan-tropical estimates of biomass at 1 km [150] and 500 m [151] spatial resolution have been demonstrated in two recent studies. While world firsts in attempting biomass estimation at global scale, these data are not suited to estimation of carbon stocks at country scale for REDD+ monitoring [152].

Optical capabilities

Optical data are not useful for stand-alone biomass estimation. The combination of optical and SAR data is recommended. Spectral indices derived from satellite optical data (e.g., Leaf Area Index, LAI; fraction of absorbed photosynthetically active radiation, fAPAR) have demonstrated potential to estimate AGB in low biomass forests, but are not yet considered operational [153]. Such an approach demands a consistent time-series and rigorous calibration. Simultaneous acquisition of ground data is essential.

National operational examples

- Australia's NCAS: The only satellite based national operational system for estimating carbon emissions. The integration of Landsat derived LULC and change maps, meteorological data, soil type and carbon and land management information in the Full Carbon Accounting Model (FullCAM) facilitates the estimation of greenhouse emissions arising from anthropogenic activity [82]; [6]. The outputs support national reporting requirements for the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol Greenhouse Gas Inventory.

Promising R&D case studies

- Finland: Landsat data are used to estimate biomass locally in combination with a full national forest inventory (NFI). NFI point measurements in direct proximity to a Landsat pixel are weighted the strongest, and so Landsat biomass is largely interpolated from local ground measurements. The density of ground measurements required is the subject of on-going research.
- Democratic Republic of the Congo: ESA GMES Service Element on Forest Monitoring (GSE FM) REDD Pilot Project in the DRC (http://www.redd-services.info/content/gse-fm-redd). Combination of MODIS, FAO allometrics and ecological zone data to map AGB [41]. Field validation is underway.
- Laos: Linear regression analysis and probability method (unsupervised clustering and fuzzy estimation) applied to predict AGB using ALOS AVNIR-2 data [222]. RMSE of 33.6 t/ha (44.2 % of mean biomass). The combination of AVNIR-2 and ALOS PALSAR data did not improve biomass estimation compared to using AVNIR-2 data alone.

Radar capabilities

Although SAR has demonstrated potential for retrieval of AGB, there are limitations arising from rapid saturation of the signal at low levels of AGB, terrain, rainfall and soil moisture effects, localised algorithm development focussing on a single biome or mono-species stands, and lack of consistency in estimates as a function of sensor parameters. Calibration of the retrieval algorithm is dependent on reliable ground data, collected under a range of environmental conditions. As such, there is limited transferability of algorithms within and between different forest structural types and, as yet, no reliable means of retrieving AGB [83]. SAR based retrieval of AGB has been more successful in temperate forests compared to tropical forests, due largely to fewer species and lower biomass [209]. Increased sensitivity has been achieved using ratios or correlations between multi-frequency, multi-polarisation backscatter and biomass components [209]. Alternative approaches, including SAR interferometry, polarimetric interferometry, tomography and integration with LiDAR and other data are the focus of current investigations. Bi-static SAR presents a novel approach to estimation of global forest height [184], and studies are currently underway using data from the TanDEM-X mission and simulated future L-band missions.

SAR has demonstrated capacity to quantify biomass up to a certain level, depending on the frequency used. Once saturation of the signal is reached, the data are no longer useful for biomass estimation [154]; [152]. Cross-polarised backscatter demonstrates greater sensitivity to forest biomass than co-polarised backscatter, however, the use of multiple polarisations is recommended for use in retrieval algorithms [209]. L-band SAR is useful for discriminating regrowth stage and estimating biomass in low biomass (40-150 t/ha) forests. Dual polarisation and dual-season coverage is required. C-band SAR is only useful in very low biomass forests (30-50 t/ha). The shorter wavelength does not penetrate further than the leafy canopy [209]. Texture analysis of multi-temporal, high resolution C-band data may provide some useful input [209].

ESA has recently approved the BIOMASS mission, a P-band interferometer which will provide global scale estimation of ABG in the 2020timeframe. P-band SAR can facilitate biomass estimation in high biomass (100-300 t/ha) forest.

Sub-national demonstrations

Biomass estimating using SAR requires sophisticated processing and extensive ground calibration, and while the research is progressing, there are few demonstrations at sub-national scale. Successful demonstrations have largely relied on GFOI non-core data streams, including airborne (GeoSAR) and satellite radar (ALOS PALSAR, ENVISAT ASAR).

- Eastern Australia: Relationships established between ALOS PALSAR L-HH and HV backscatter and field measured AGB led to the production of an interim AGB map (Figure 18; [83]). Validation underway. Improvements likely through the integration of Landsat and ICESat data products.

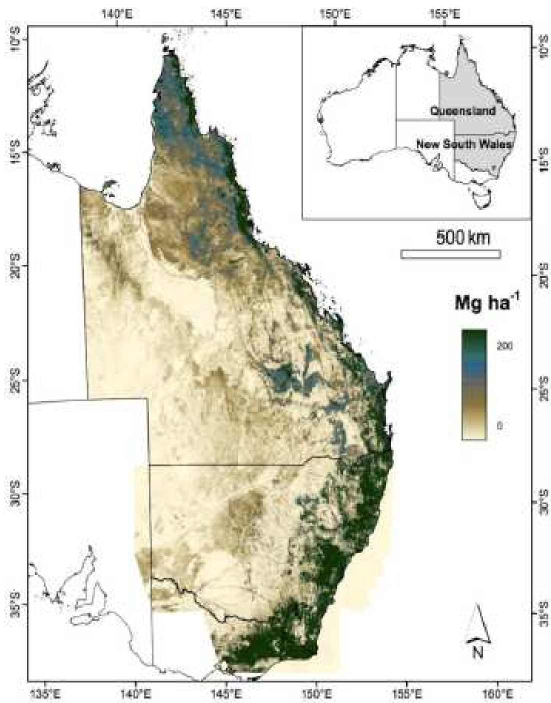


Figure 18 Total AGB for eastern Australia as estimated from ALOS PALSAR L-HV and relationships with field data [75].

- Mexico: Wall-to-wall AGB map produced using ALOS PALSAR data acquired in 2008 at 15 m spatial resolution [18].
- North-eastern USA: Inversion of semi-empirical model calibrated for ALOS PALSAR FBD images to estimate biomass [84]. Retrieval accuracy for HV intensity data was consistently better than for HH. Weighted combinations of single-date biomass estimates in a multi-temporal stack significantly improved performance. RMSE of 12.9 t/ha (R2 = 0.86) compared to forest inventory.
- Boreal forest: Model based estimation of growing stock volume (GSV) up to 300 m3/ha using hyper-temporal ENVISAT ASAR ScanSAR images [85]. RMSE of 34.2 – 48.1 % at 1 km pixel size. GSV was improved by averaging over neighbouring pixels. Transferability of method to tropical forest requires investigation.

Promising R&D case studies

- Adamawa, central Cameroon: The European Union Framework Programme 7 (EU FP7) Collaborative Research Project Reducing Emissions from Deforestation and Degradation in Africa (REDDAF) aims to develop, test and provide improved methodologies to assess AGB using radar data. Model inversion was applied using time-series ALOS PALSAR (2007 – 2010) and field data in central Cameroon to produce AGB stratification maps [41]. Ground truth validation is on-going, with further collection of terrestrial AGB measurements in forest-savannah transition regions. Biomass assessment is limited to low biomass forests (<150 – 200 t/ha).

- Hoa Binh province, Vietnam: Map of biomass produced in an area of extensive rubber plantation using time-series ALOS PALSAR data and in situ biomass measurements [162]. Forest biomass was relatively low (<40 t/ha), and the PALSAR was useful in providing information relevant to the carbon budget and assessment of forest states (e.g., logging to regrowth). It is anticipated that the methods will be applied to whole of Vietnam.
- Borneo: Use of X- (TerraSAR-X) and L-band (ALOS PALSAR) SAR to estimate AGB in intact and degraded tropical forests [170]. LiDAR-derived biomass was used to calibrate SAR backscatter images and up-scaled to estimate biomass over a large area. PALSAR was more sensitive to biomass than TerraSAR-X, particularly in higher biomass range (>100 t/ha), however PALSAR results were less accurate in low biomass ranges due to higher variance. A multi-temporal combined X- and L-band model could predict AGB with an r2 = 0.53 and RMSE of 79 t/ha. The model was considered valid up to 307 t/ha with an accuracy requirement of 50 t/ha.
- Fly River, PNG: Dual frequency (X- and P-band) interferometric SAR data acquired by the airborne GeoSAR instrument presents a unique opportunity to estimate both near ground and canopy height. The difference in X- and P-band heights yields a surrogate vegetation height, which can be used to retrieve tropical forest biomass (Figure 19; [86]). The technique permits the estimation of high biomass (> 150 t/ha), not previously possible using radiometric techniques alone. The combination of GeoSAR for producing a high resolution, accurate baseline of AGB, against which change in carbon stocks can be monitoring using satellite SAR (e.g., PALSAR-2) is suggested.
- Tanzania: AGB stratification estimation using ALOS PALSAR HV data acquired between 2007 – 2009 [41]. Future use of LiDAR and VHR WorldView-2 data.
- Laos: Linear regression analysis and probability method (unsupervised clustering and fuzzy estimation) applied to predict AGB using ALOS PALSAR data [222]. RMSE of 40.1 t/ha (52.8 % of mean biomass). Estimation with PALSAR produced a lower variability of the biomass prediction than AVNIR-2 data. The contribution of HH in the biomass prediction was less than for HV. Performance may be improved using multi-temporal SAR acquisitions.

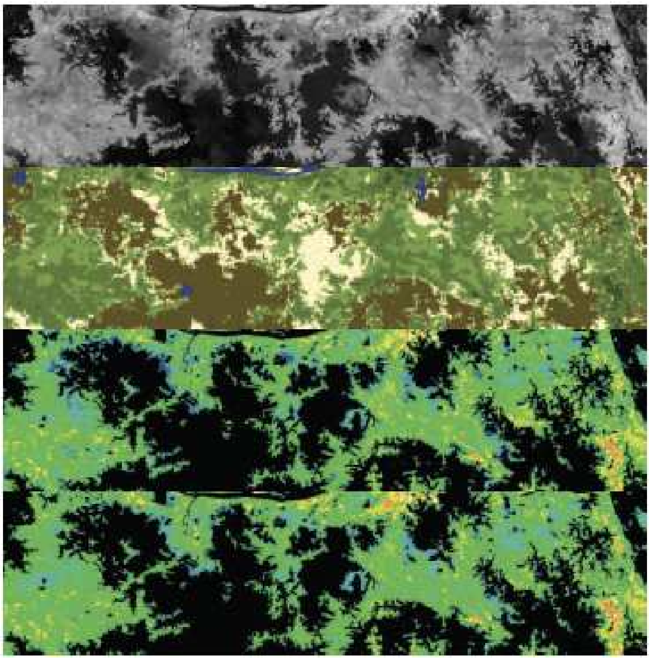


Figure 19 Biomass estimation in Fly River, PNG. Top to bottom: Surrogate vegetation height within segments, segment-based classification (forest in green), biomass map derived from modelling approach, and biomass derived from surrogate height alone [86].

LiDAR capabilities

Airborne LiDAR data have been demonstrated to produce more precise biomass estimates than any other remote sensing technique. Although LiDAR is one of the few remote sensing techniques that are used operationally to produce commercial information products for operational management of the forest resources [155], large-scale demonstrations are few in number. Wall-to-wall estimation of biomass and other biophysical properties are typically restricted to areas smaller than, say, 10,000 km^2 in size (e.g., [189]; [190]). However, the massive research effort over the past 15 years[188]; [191]; [192]; [193] and the fact that the technology is used operationally has demonstrated potential of the technology that easily can be capitalized upon even in regional and nation-wide surveys.

Wall-to-wall LiDAR may fill a niche in local REDD projects within the countries. However, for GFOI a large-scale approach is more at the core of the task. Thus, applications that can produce precise estimates of biomass and at reasonable costs should be identified. Considerable effort has been undertaken over the past 7-8 years to develop and test sampling designs for regional biomass estimation which rely on a sample of individual LiDAR strips and coincident field sample plots. The LiDAR sample may cover 5-10 % of the target area or even less – depending on the available resources and the precision requirement. One can also envision a design by which LiDAR strip samples are combined with coincident field plots and complete coverage SAR data. The latter topic is also touched upon in the next section (Interoperable capabilities).

Terrestrial Laser scanning (TLS) also demonstrates potential for rapid, cost-effective measurement of AGB for calibration/validation of existing methods of biomass inventory. TLS also provides accurate measurement of, and characterisation of the variability in forest structural parameters, including trunk diameter, stem density and height, which can improve the accuracy of biomass estimates. TLS measurements also support plot cartography, species recognition, wood volume estimates, gap fraction analysis, stand value and woody quality assessment, and other ecological applications [176]. More time-efficient sampling means greater sample size. TLS can also be deployed whenever needed to capture disturbance arising from, for example, destructive harvesting or storm damage. Full-waveform measurements from overlapping scans allow the stand to be reconstructed in 3D, for virtual direct measurement of biomass. Underlying woody debris, including fallen logs and branches, is also observed, and may be included in biomass estimates.

Promising R&D case studies

- Hedmark County, Norway: Several studies in a 27,000 km^2 boreal forest area where an 8% sampling fraction LiDAR strip sample was combined with ground samples to estimate biomass [93]; [94]; [95]; [96]; [97]; [91]. A number of different statistical estimators were derived and demonstrated. Some of the estimators (design-based, model-assisted) assumed a probability sample of field plots, while some (model-based) only assumed availability of a correctly specified model. A sampling simulator was also developed which was used to test the validity of analytically derived statistical estimators and to compare sampling designs and estimators. The results showed great improvements in precision of the LiDAR-assisted biomass estimates. LiDAR sampling was also cost-effective compared to a pure field-based survey. The derived estimators are valid also for similar designs if applied in other regions, like in the tropics.
- Alaska: Similar studies as those conducted in Norway have also been carried out in interior Alaska (all studies in boreal forest areas <10,000 km2 in size; [98]. Many of the same estimators were used and similar results were obtained as in Norway.
- Norway: direct estimation of foliage biomass from TLS scans and comparison against destructive sampling [158]. Results revealed that foliage biomass can be estimated with higher accuracy than by using allometric models.
- Southern Ontario, Canada: comparison of tree-level measurements of stem location, tree height, DBH, stem density and timber volume in red pine plantation and mixed deciduous forest using TLS and field mensuration data [177]. All parameters were measured or derived successfully using the TLS system. A slight systematic underestimation of mean tree height was observed, due to canopy shadowing and suboptimal scan sampling distribution. Timber volume was estimated to within 7 % of ground estimates. Locating and counting trees in the LiDAR point cloud required field validation and some subjective interpretation. The use of TLS was considered promising for consistent forest metric assessment, but further development of automatic feature identification and data extraction techniques was warranted.

Interoperable capabilities

To achieve operational status, high resolution estimates of forest carbon stocks and associated spatially explicit uncertainty are required. Multi-sensor approaches (optical-LiDAR-SAR) combined with ground measurements are the way forward. Further research is required on consistent retrieval of AGB using (i) pixel based methods for wall-to-wall, regional scale mapping, and (ii) biomass-sampling approach with extrapolation over large areas for national-global mapping.

Sub-national demonstrations

There is untapped potential for AGB estimation through the integration of optical, SAR and LiDAR data. Optical data is unsuitable alone; SAR is useful up to certain level of biomass; and LiDAR, while capable of fine resolution measurement of forest carbon density [156]; [150] is limited to small-scale operations. Ideally, a future space-borne LiDAR would provide the capacity for global scale forest carbon stock assessment.

- Continental US: An empirical modelling approach combining national forest inventory data (e.g., USDA-FS plot height and biomass metrics), SRTM and Landsat ETM+

data was adopted to produce a baseline national estimate of AGLB [157]; [87]. Comparison with multi-scale reference data revealed an RMSE of 55 Mg/ha (plot scale), 19 Mg/ha (hexagon), 14 Mg/ha (county) and 12 Mg/ha (State). The biomass map is the first of its kind at national scale.

- Conterminous USA and Alaska: Extent and distribution of forest biomass [185]; derived by modelling of field plot biomass data and more than 60 geospatially continuous predictors layers (e.g., DEMs and derivatives, MODIS data, vegetation indices, class summaries from the National Land Cover Data set, ecological zones and climate data). Modelling was performed using Cubist/See5 and Imagine software. Correlation coefficients for biomass ranged from 0,73 in the Pacific northwest to 0.31 in the southern region. A tendency to over-predict areas of small biomass and under-predict areas of large biomass was observed. Produced by USDA Forest Service (USFS) Forest Inventory and Analysis (FIA) Remote Sensing Band (RSB; http://webmap.ornl.gov/biomass/biomass.html).
- Colombia: Carbon stocks mapped through the integration of GeoSAR, ALOS PALSAR and Landsat data [18]. Validation underway.
- Borneo: A biomass stratification map was produced using a combination of 2008 ALOS PALSAR and ICESat GLAS height data at 50 m spatial resolution (Figure 20; [41]). Validation underway using field observations acquired in support of biomass inventory.
- Mexico: AGB stratification maps produced using ALOS PALSAR, ENVISAT ASAR and Landsat data [41].
- Guyana: AGB stratification map produced using ALOS PALSAR and Landsat data [41].
- Amazon basin: Decision tree classification of JERS-1, SRTM, QSCAT and MODIS derived metrics (LAI, NDVI and percentage tree cover), plot AGB and climate data to determine spatial distribution of biomass [88]. Overall accuracy of 81 %, with the lowest accuracies associated with the highest biomass classes. High resolution data may improve the correlation with field plot data, and so reduce the uncertainty in biomass estimates.
- Nepal: LiDAR-assisted AGB estimation has been applied at sub-national scale. LiDAR overcomes the saturation problem inherent to satellite-based biomass estimation. By integrating LiDAR with satellite data and field reference, an accurate and affordable monitoring solution for tropical forest inventory is presented [180]. LiDAR-Assisted Multi-source Programme (LAMP) combines field sample plots with tree-level measurements, LiDAR data over sample areas (covering 1-5 % of total area), and wall-to-wall satellite data to estimate AGB. Results are validated using an independent set of field plot data. LAMP comprises a two-step approach: first, forest variables related to biomass are estimated from LiDAR using field data as reference (sparse-Bayesian regression); second, the LiDAR estimates are used to interpret high (e.g., RapidEye) to medium (e.g., Landsat-7, ALOS AVNIR-2) resolution satellite data. Radiometrically normalised satellite imagery can be used in backward and forward model estimates of AGB. LAMP has been successfully demonstrated at different scales in Nepal, Ghana and Lao PDR (http://www.arbonaut.com; [180]).

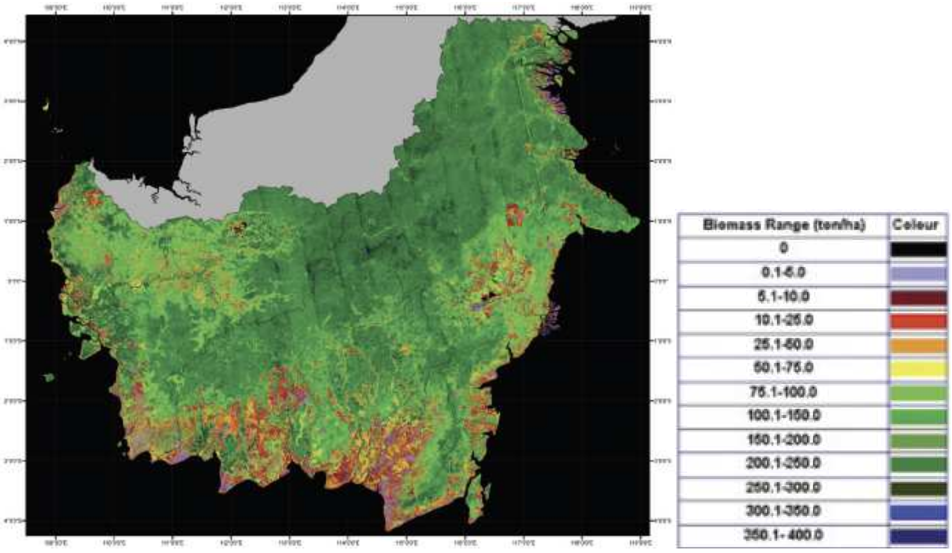


Figure 20 Biomass stratification map for Borneo based on ALOS PALSAR and GLAS data ([41]; http://www.geo-fct.org/pd-team-documents).

<u>Promising R&D case studies</u>

- o Colombian Amazon: Carbon stocks are predicted using a combination of LiDAR derived elevation, fractional canopy cover and terrain ruggedness, and extrapolated over a 16.5 million ha region (Figure 21; [90]). Uncertainty of 14.6 % at 1 ha resolution. Regional maps derived from stratification and regression had 25.6 % and 29.6 % uncertainty.

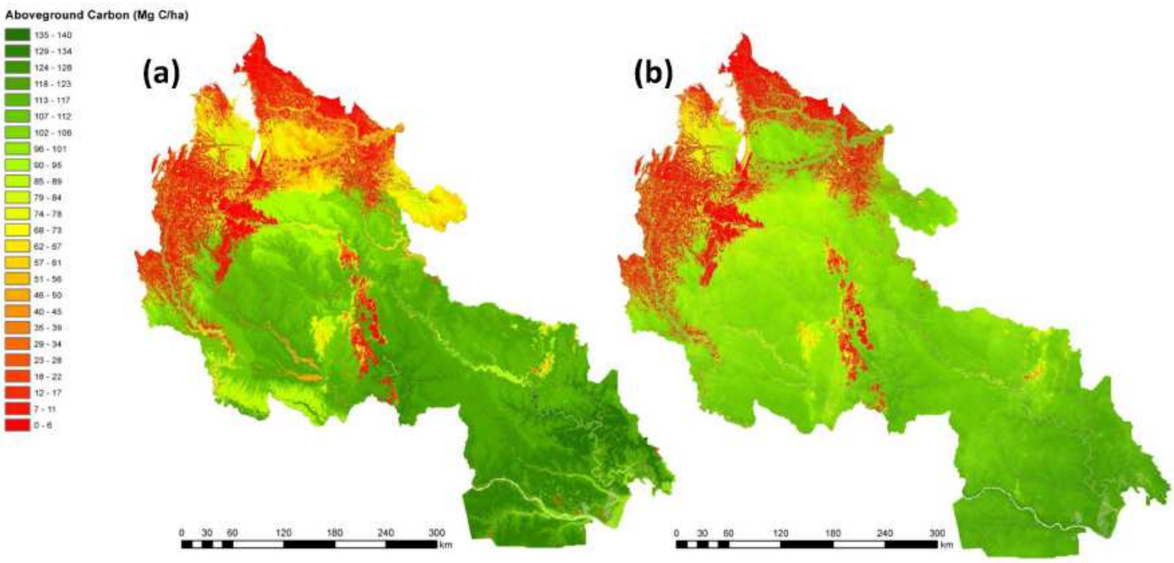


Figure 21 Above ground carbon density across the Colombian Amazon generated using LiDAR data and (a) regional stratification with elevation, fractional cover of photosynthetic vegetation and terrain ruggedness, and (b) regression analysis with elevation and fractional cover of photosynthetic vegetation [90].

- o Howland, Maine: LiDAR derived height indices used to predict biomass, and subsequently determine correlations with ALOS PALSAR data [99]. PALSAR quad-pol and dual-pol data could predict the LiDAR biomass samples with R2 = 0.63 – 0.71

and RMSE of 32 – 28.2 Mg/ha up to biomass levels of 200 – 250 Mg/ha. Multiple channels and polarisations of SAR and temporal acquisitions are required for biomass retrieval. The height of the scattering phase centre at C-band was an important variable, and means of calculating this using data from future SAR sensors should be investigated. The correlation between biomass and LiDAR waveform indices may be affected by species and structure, and also warrants further investigation.

- Gabon: Combination of ALOS PALSAR, ICESat GLAS and ground data to map biomass at 100 m resolution [89]. Uncertainty of 25 %, arising from the use of a generic tropical allometric equation, use of GLAS to estimate Lorey's height, and necessity of separating landscape into discrete classes.
- Alaska: Samples of airborne LiDAR strips with coincident ground samples and complete coverage satellite SAR (ALOS PALSAR) were used to obtain biomass estimates for a study area in boreal forest in Alaska [92]. This case study was the first application where a combination of different types of remote sensing data, some with complete coverage and some with partial coverage collected as carefully designed samples following a rigorous probabilistic design, was demonstrated for biomass estimation for a region. Work is currently on-going to expand on this approach by using dense time series of SAR data and rigorous statistical estimators (and variance estimators) designed specifically for situations where some auxiliary (remote sensing) data have complete coverage and some just are collected as samples. The results are promising (Andersen pers. comm.).
- Harvard forest, Western Massachusetts: Comparison of repeat-pass ALOS PALSAR quad-pol observations and full waveform LiDAR collected by LVIS for vegetation characterisation [160]. The study demonstrated the potential to derive LiDAR-based estimates of biomass over a large region (using ground validation measurements; mean error of 33 Mg/ha), and develop a relationship between radar backscatter and LiDAR derived biomass. The variation in the radar-LiDAR signature was quite large however, and inverting the model would result in large uncertainty. Future R&D will investigate other ALOS observing modes for estimation of vegetation characteristics.
- Boreal forest, Southern Finland: Comparison of AGB and stem volume estimation accuracy derived from airborne LiDAR and TerraSAR-X stereo radargrammetry-derived point-height metrics [173]. LiDAR AGB estimation accuracy values (RMSE) are 21.9 % (32.3 t/ha), and 29.9 % (41.3 t/ha) when using TerraSAR-X stereo radargrammetry. The study concluded that the radargrammetry approach is a promising technique for large area forest AGB mapping when an accurate LiDAR-based DTM is available.
- Ludikhola, Charnwati and Kayerkhola Watersheds, Nepal: Estimation of tropical broadleaved forest carbon stock using WorldView-2 and airborne LiDAR data [181]. A canopy height model (CHM) was developed using LiDAR data. The CHM and satellite data were segmented, tree crowns were delineated and classified to species. A relationship was determined between crown projection area (CPA), tree height and carbon stock for different tree species, and used in multiple regression to estimate carbon stocks. While forest cover classification results were high (82 – 94 %), tree species classification accuracy decreased with increasing number of species (67 % with 7 species to 86 % with 2 species). Carbon stock estimation accuracy ranged between RMSE 24.85 – 49.75 % (r = 0.76 – 0.94).
- Terai Arc Landscape (TAL), Nepal: LiDAR-Assisted Multi-source Programme (LAMP) approach applied to AGB estimation in TAL, Nepal [204]. A sparse-Bayesian method was used to calibrate 738 field plot measurements with LiDAR metrics. LiDAR estimates were used as simulated ground truth and regressed with Landsat-5 TM derived textural variables and vegetation indices to calculate AGB over the whole

study area. The accuracy of the LiDAR model was verified using independent field plot data (RMSE 0.17, r^2 0.92). The biomass/carbon map was validated using LiDAR-based carbon estimates (RMSE 0.42, r^2 0.48). It is anticipated that the LAMP approach will assist Nepal in the REDD+ process and future forest monitoring activities.

- Nepal: Comparison of cost and accuracy between the LiDAR-Assisted Multi-source Programme (LAMP) and field-based Forest Resource Assessment (FRA) in the 23,300 km^2 Terai Arc Landscape (TAL) of Nepal [187]. Model-based LAMP was applied by integrating 5 % LiDAR sampling, wall-to-wall RapidEye and field sample plot data. Design-based FRA was found to be more cost-effective (US$ 0.22/ha) compared to the LAMP approach (US$ 0.28/ha) for collecting baseline data, but administrative costs were significantly higher (US$ 0.26/ha). The cost of forest monitoring is highly dependent on national capacity. LAMP was more cost-effective for subsequent forest inventory. Mean errors in LAMP-derived mean biomass estimates were also significantly smaller at all spatial resolutions. The spatial accuracy of LAMP was considered adequate for AGB estimation in community forests with an average size of 150 ha. The FRA method facilitates estimation of a large number of variables, ranging from tree-level characteristics to biodiversity and soil, however, LAMP provides biomass and carbon stock estimates suitable for IPCC Tier 3 reporting which is difficult to achieve with field based multisource inventory [187]. It was recommended that LiDAR sampling intensity and field plot measurement be analysed further.
- Ghana: Two biomass maps of Ghana produced for 2008-2009 at 250 m and 100 m spatial resolutions with associated uncertainties of 3 % and 5 % respectively (http://www.forest-trends.org/documents/files/doc_2837.pdf). Existing and new field plot measurements were acquired to calibrate and validate the maps. The maps were derived by combining field plot data, ALOS PALSAR, MODIS and ICESat GLAS data. The maps present a useful baseline of carbon stocks against which future stock changes can be assessed.
- Western Ghana: A sampling design based on LiDAR strip sampling was developed for Ghanaian forests to support field plot sampling for biomass estimation [194]. LULC was first mapped using ALOS AVNIR-2 and DMC data, and further stratified using existing GIS data (ecological zones). LiDAR sample strips were then acquired systematically so that all forest and land use categories were represented. This necessitated a LiDAR sampling intensity of around 5.1 % of the total area. The study concluded that the systematic LiDAR sampling design was representative of the variation in AGB densities, and so provides sufficient a-priori data, together with the LULC product, for designing efficient field plot sampling over the seven identified ecological zones [194].

Annex B.12 Change in Above-ground Biomass

Map showing the change in above-ground biomass (AGB) in stratified vegetation/land cover classes. It can be used to derive emission factors for reporting purposes. The product will cover AGB changes from, for example, forest to non-forest or regrowth that falls below the threshold for forest.

There are very limited EO based examples of estimating AGB change. There are two approaches to estimating AGB change using remote sensing. First, you can use two observations in time (T1 and T2) with coincident field data to model change in biomass directly as differences at pixel level corresponding to remote sensing observables at T1 and T2. Second, you can model and estimate biomass for T1 and T2 separately and take the difference. These methods are still considered in the research domain.

Radar capabilities

Repeat acquisition of SAR data, together with field plot data can be used to estimate change in AGB over time. A consistent time-series of observations is important for quantifying change.

<u>Promising R&D case studies</u>

- central Siberia: Change in forest cover in terms of biomass loss and gain was estimated using ALOS PALSAR data (acquired in 2007) as compared to an existing forest map (derived from ERS-1/ERS-2 and JERS-1 data from 1997; [103]). First, forest cover was mapped using the PALSAR data. Training polygons were digitized from VHR optical data. Forest classes identified included low (<50 m3/ha), medium (50 - 80 m3/ha) and high (>80 m3/ha) biomass. Second, forest maps were compared on a pixel basis and a map of the area of forest biomass loss and gain was generated (Figure 22). Medium and high biomass classes were merged prior to change detection to reduce classification uncertainty.
- Mozambique: Time-series ALOS PALSAR and field plot data are combined using regression and bootstrapping to generate biomass maps (Figure 23; [171]). The derived maps can detect changes in AGB as little as 12 MgC ha-1 over 3 years with 95 % confidence, allowing characterisation of biomass loss from deforestation and degradation at a new level of detail.
- East Anglia, UK: Two empirically based methods of monitoring forest growth over a 9-year interval using fully polarimetric airborne SAR (AIRSAR; acquired in 1991) and airborne repeat-pass L-band fully Polarimetric InSAR SAR (E-SAR; acquired in 2000) were compared [182]. In the first approach, height and volume change were estimated using mean L-band stand backscatter difference between the two image dates. The estimation accuracy was 0.23 m for height change and 15 m^3 ha^{-1} for volume change for those stands below saturation point. In the second approach, height change was calculated by differencing the estimated stand heights in 2000 and 1991. Better results were obtained using the first approach. The study concluded that multi-temporal L-band SAR data can be used to monitor and quantify growth rates of young stands by correlating backscatter change to stand height change. Signal saturation is limiting for accurate growth monitoring in mature stands however.
- East Anglia, UK: Tree growth estimation of Corsican Pine stands from multi-temporal spaceborne L-band SAR [183]. Incremental growth was estimated from the change in backscatter between a SEASAT image from 1978 and a JERS-1 image from 1997, and compared to expected tree growth from forestry models. An RMSE of 3.4 m was obtained when a linear model was applied. The accuracy of the retrieval algorithm was dependent on minimum forest stand size. The study demonstrated the potential

of multi-temporal L-band SAR for detecting incremental biomass in support of sustainable forestry.

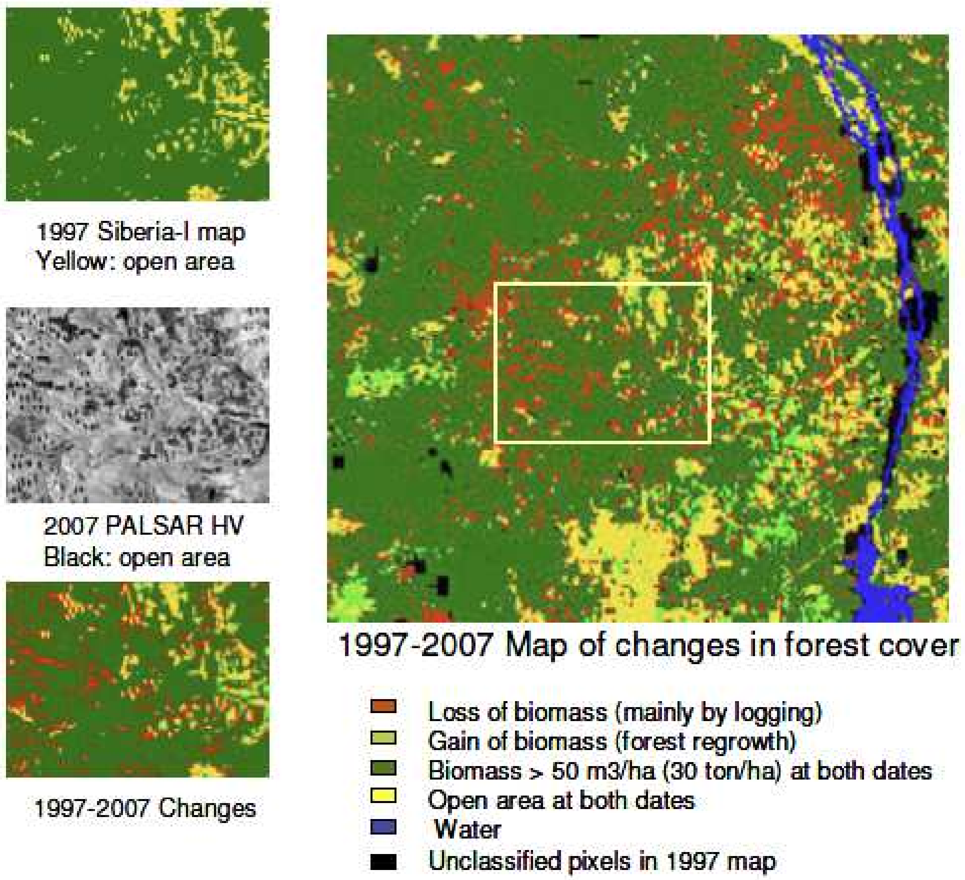


Figure 22 Map of changes in forest biomass over a ten year period (1997-2007) in central Siberia [103].

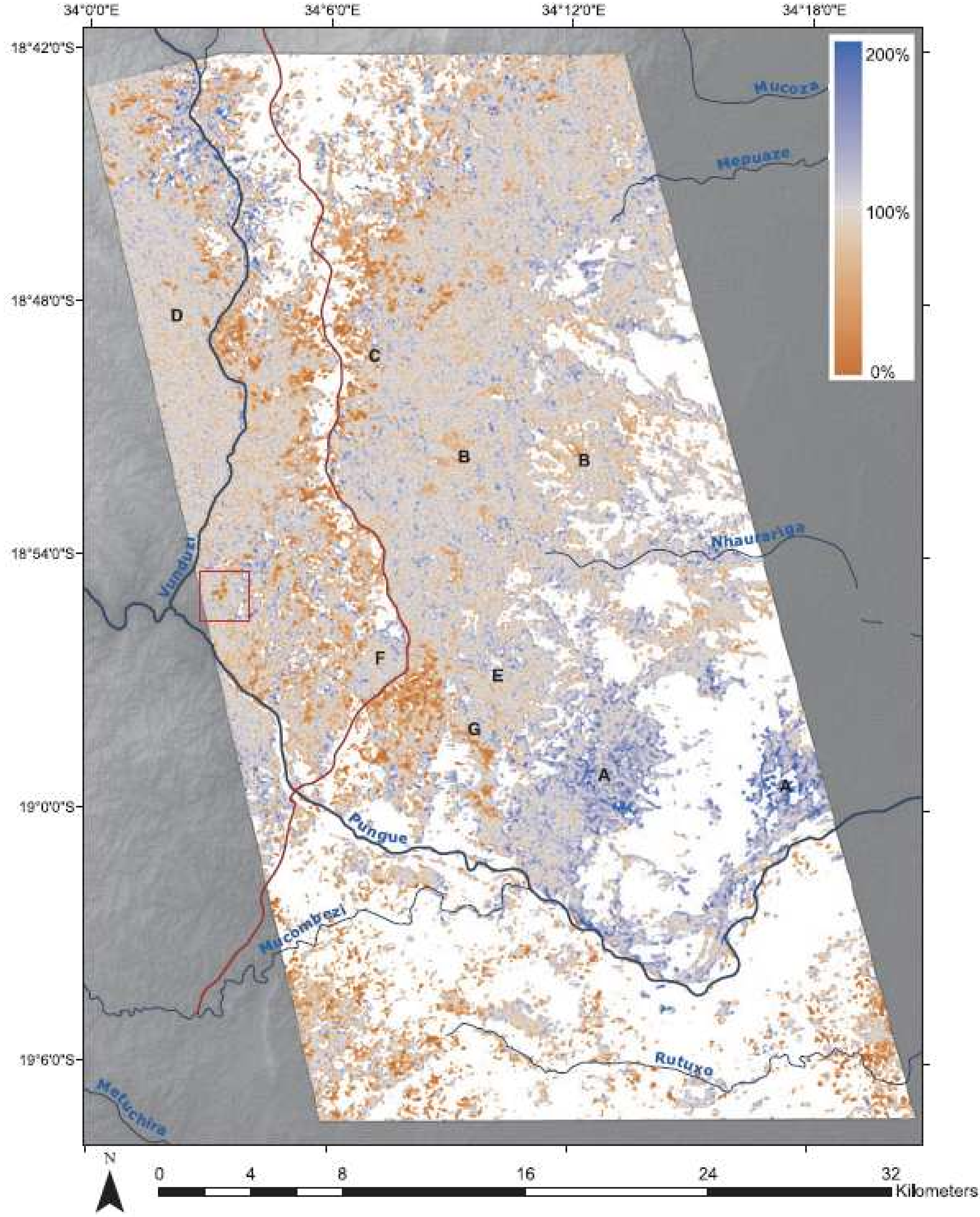


Figure 23 Map of carbon stock change in Mozambique study area [171]. AGB in 2010 is shown as a percentage of AGB in 2007. Values >100 % indicate areas of biomass gain (blue) and values <100 % indicate areas of biomass loss (red).

LiDAR capabilities

To date, there are fewer than a handful of studies that have addressed the issue of modelling and estimating change in AGB using multi-temporal LiDAR data. However, there are indications of strong relationships between change in AGB and change in fundamental metrics derived from LiDAR data. Most studies conducted to date have been carried out in boreal or temperate forests, although some examples from tropical forests are about to emerge in the scientific literature.

With access to LiDAR metrics such as canopy height and canopy density and repeated observations of field plots, change in AGB can in principle be estimated either (i) by modelling and estimating AGB as a function of LiDAR metrics at time 1 and time 2 separately and then estimating the change as the difference between two individual estimates, or (ii) modelling the change in AGB directly as a function of LiDAR metrics from time 1 and 2 combined (or differences in LiDAR metrics). It remains an open question as to which of the two methods is best suited for change estimation. However, both methods can be applied in situations where a probability sample of repeated field plots is available, such as with a continuous NFI program (design-based estimation), or if the field sample is acquired under a non-probability design (model-based estimation) for reasons such as limited ground access in remote areas or security concerns.

Complete coverage (wall-to-wall) LiDAR is expensive and hardly an option for purposes other than local REDD projects within countries. For larger areas such as districts, provinces and nations, sampling with LiDAR over coincident ground plots and possibly combined with complete cover multi-temporal SAR data is indeed a viable option, as it is for estimation of AGB (see previous sections). Depending on the level of management and/or forestry operations, LiDAR acquisition need not be repeated for around 10-15 years in forest that does not change much (Arbonaut Ltd., Pers. Comm.). New satellite data can be integrated using LiDAR-assisted methods for estimation of AGB change.

<u>Promising R&D case studies</u>

- Hirkjølen experimental forest, Norway: Based on a dataset of 52 field plots and coincident LiDAR data measured twice over a four year period, three approaches for using LiDAR to model and predict AGB change were analysed [165]. For each approach, the model predictor variables were either height percentiles or differences in height percentiles between time 1 and time 2. The first approach was indirect and entailed constructing a model of the relationship between AGB observations and height percentiles aggregated for both years. AGB change was then estimated as the difference between the model predictions for the two years. The second approach was direct and entailed constructing a model of the relationship between AGB change and differences in LiDAR height percentiles. The third approach consisted of constructing a model of the relationship between the average annual relative growth rate between time 1 and time 2 and corresponding average annual relative change in LiDAR height percentiles. Models based on the second and third approach that directly predicted change variables were superior to the first approach that only indirectly predicted change, and models based on the second approach that predicted actual change were slightly superior to models based on the third approach that predicted relative change. This study was among the very first to demonstrate that change in an important climate change variable, AGB, can be predicted using change in LiDAR metrics.
- Boreal forest, Norway: In a case study from a boreal forest area in Norway, it was demonstrated that categories of AGB changeover an 11 year period with different management activities could be distinguished, and that population estimates of AGB change could be calculated using observations for a sample of field plots and wall-to-wall LiDAR data [78]. Based on changes over the entire time period, three activity classes were defined: (i) recent clear cut representing deforestation, (ii) thinned representing forest degradation, and (iii) untouched representing natural growth with no harvest. Each of 176 plots was then assigned to a single activity class and a classifier was trained using the plot activity class assignments and corresponding LiDAR metrics from time 1 and time 2 and used to assign every 200 m2 grid cell

("pixel") over the area to an activity class. For each class, different types of models for the relationship between AGB and LiDAR metrics for time 1 and 2, respectively, or for change in AGB as a function of change in LiDAR metrics were constructed. These models were subsequently used to predict AGB change for every pixel of the various activity classes, and finally the change in AGB for the entire area was estimated by combining the LiDAR predictions and the observed AGB change on the plots using design-based, model-assisted estimators.

The results were compared to corresponding estimates obtained using only field data. The standard errors for the activity class area estimates were 18 - 84 % smaller than standard errors obtained using only the field plot data. Similarly, standard errors for the activity class mean AGB change estimates were 43 - 75 % smaller when obtained using the LiDAR data. The study demonstrated that deforested, thinned and degraded, and unchanged forest areas can be discriminated and that change in AGB for those areas can be precisely estimated using LiDAR metrics. Of more importance, the study was the first to use statistically rigorous methods to estimate and quantify bias, to estimate precision, and to quantify the utility of auxiliary LiDAR data for increasing the precision of estimates for areas consisting of multiple grid cells (pixels).

- Northern Idaho: Use of discrete return airborne LiDAR for quantifying biomass change in mixed conifer forest [163]. Random Forest algorithm used to impute AGB pools of trees, saplings, shrubs, herbaceous plants, coarse and fine woody debris, litter and duff using forest inventory data and LiDAR-derived metrics. Separate predictive tree AGB models were developed using 2003 and 2009 field and LiDAR data (Figure 24). Biomass change was estimated at the plot, pixel and landscape levels by subtracting the 2003 from 2009 predictions. The results demonstrated the potential of repeat LiDAR surveys for accurate, high resolution, spatially explicit quantification of biomass and carbon dynamics.
- Boreal forest, Saskatchewan, Canada and Eucalyptus forest, Tumbarumba, NSW Australia: Multi-temporal LiDAR and field plot data used to model changes in carbon storage in jack pine and eucalyptus forests [164]. Predictive models were developed using LiDAR-derived vegetation metrics and applied across each study area. AGB was converted to above-ground carbon using a multiplier of 0.5. An expansion factor was applied and a below-ground biomass component added so that AGB change estimates could be compared with flux tower productivity estimates. The best model fit at plot level was obtained using the interquartile range (r2 = 0.96, RMSE = 3.2 t C/ha in jack pine sites, and r2 = 0.71, RMSE = 37.6 t C/ha in eucalyptus sites).

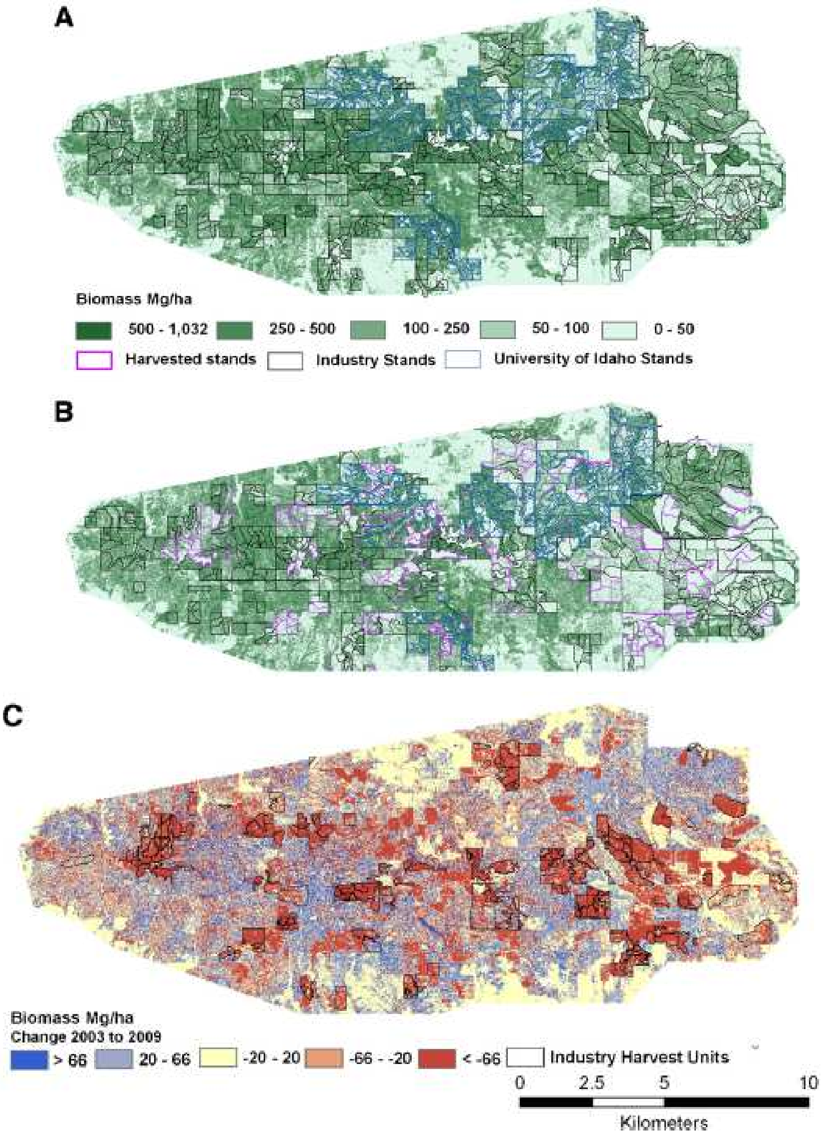


Figure 24 Predicted tree AGB in 2003 (A) and 2009 (B), and the change in AGB produced by subtracting A from B (C). Estimates derived from discrete return LiDAR [163].

Annex B.13 Evaluation of operational status: Degradation and AGB

Table B.3 Evaluation of operational readiness of GFOI Degradation and AGB information products.

Code	National operational examples	Sub-national demonstrations	Promising R&D case studies	EO data availability	Additional R&D needs	GOFC-GOLD Reference
Forest stratification	-Copernicus, pan-European	-EC JRC Europe forests -State-wide veg mapping, Australia - Caribbean		**Core:** Landsat-7	- Time-series and seasonal dynamics -Texture metrics - Species distribution models - Scaling RS data - Consistency across biomes -SAR-optical integration -SAR-SAR integration -LiDAR and InSAR structural classification -Future hyperspectral	- Stratification based on carbon content of specific forest types
		-EC JRC TREES - South America -State-wide veg mapping, Australia -Congo	-GEO Guyana - Greece - Indonesia - Borneo - Minnesota - Brazil - Costa Rica - India - Ecuador	Non-core: SPOT VGT SPOT-5 IRS AVHRR ALOS PALSAR Quickbird ENVISAT ASAR RADARSAT SRTM		
Degradation and/or enhancements of C stocks	-INPE DEGRAD	-LEDAPS, USA -LandTrendr, USA	- Ethiopia	Core: Landsat-7	-Data integration - Pixel mining and trajectory segmentation -Regrowth mapping using optical-SAR integration - VHR data -Establishing reference levels - LiDAR profiles	- Direct identification of canopy gaps and clearings - Indirect mapping of roads & log decks - Very High spatial (<5 m) & temporal resolution required - Annual detection to account for old growth forest & burned areas - Image enhancement & spectral unmixing techniques - Change detection - SAR for fire related monitoring
			-Appalachian proj -Queensland, Australia - Brazil - Gabon and D.R Congo - Northern Brazil - Kalimantan	Non-core: MODIS ALOS PALSAR AIRSAR JERS-1 LIDAR Quickbird TerraSAR-X TanDEM-X		
Degradation Type Map	-INPE DEGRAD		-Manaus, Brazil	Core: Landsat CBERS-2	-Land use history from optical data -Optical-SAR integration - Automated identification of degradation type - Fractional cover and spectral indices - Change detection using VHR data	
			-Amazon proj -SE Norway -Cameroon -Central African Republic -West Colombia - Panama - D.R Congo	Non-core: IKONOS SPOT-4 TerraSAR-X LiDAR COSMO-SkyMed ALOS PALSAR		

<table>
<tr><th colspan="7">Table B.3 Evaluation of operational readiness of GFOI Degradation and AGB information products.</th></tr>
<tr><th>Code</th><th>National operational examples</th><th>Sub-national demonstrations</th><th>Promising R&D case studies</th><th>EO data availability</th><th>Additional R&D needs</th><th>GOFC-GOLD Reference</th></tr>
<tr><td rowspan="2">Above-Ground Biomass Estimates</td><td>-NCAS, Australia</td><td></td><td>-Finland proj</td><td>Core:
Landsat-7</td><td rowspan="3">-Allometrics
-Sampling designs and estimators combining LiDAR and ground samples and SAR
-Stratification using LiDAR
-InSAR and POLInSAR
-Transferability of methods (structural types, boreal to tropical)
- TanDEM-X tree height
-Optical-SAR-LiDAR integration
- Stratification using LiDAR
- Joint estimation using SAR and LiDAR
- Calibration of SAR using LiDAR
- Correlation between LiDAR and biomass</td><td rowspan="3">- Requirements for Tiers 1-3
- Tier 2 likely most used, but aim for Tier 3
- Stratification of forest types for improved carbon stock estimation
- Inclusion of other carbon pools (e.g. below-ground, dead wood) for emission reporting
- Baseline data on fire regimes & trends in emission patterns</td></tr>
<tr><td></td><td>-E. Australia
-NE USA
-Boreal forest
-Continental USA
-Conterminous USA and Alaska
-GEO Colombia
-GEO Borneo
- GEO Mexico
- GEO Guyana
-Amazon
-Nepal</td><td>-GEO Cameroon
- GEO D.R Congo
-Laos
-Fly R. PNG
-Amazon proj
-Maine proj
- Gabon
- GEO Tanzania
- Norway
- Alaska
- Harvard forest
- Vietnam
- Borneo
-Southern Finland
- Canada
-Nepal
-Ghana</td><td>Non-core:
ALOS PALSAR
ALOS AVNIR-2
ENVISAT
ICESat GLAS
GeoSAR
SRTM
MODIS
QSCAT
JERS-1
TerraSAR-X
Airborne LIDAR
TLS
WorldView-2
RapidEye
DMC</td></tr>
<tr><td>Change in Above-ground Biomass</td><td></td><td></td><td>- Central Siberia
- Hirkjølen experimental forest, Norway
- Boreal forest, Norway
- Northern Idaho
- Canada and Australia
- Mozambique
- East Anglia, UK</td><td>Non-core:
ALOS PALSAR
Airborne LiDAR
AIRSAR
E-SAR
SEASAT
JERS-1</td></tr>
</table>

Annex C GFOI Capacity Enhancement

In the course of this review, a number of additional country needs were identified that go beyond R&D. These include capacity building, data supply and institutional issues. They are listed in Table C.1 below. GFOI will provide on-going assistance to countries in these broader areas. Notable issues are addressed in the following sections.

Table C.1 Other Country Needs Identified in this Review

Topic	
General assistance with implementing forest mapping method improvements	Hyper-temporal processing
	Spatio-temporal data mining techniques
	Cloud-free compositing
	Standardised method of identifying reference levels against which countries can quantify carbon stock changes due to degradation (including use of stable ground sites and remote sensing data)
	Country specific land use transition classes
	Improved computational efficiency of integrated remote sensing data, in situ measurements and models for carbon stock estimation and emissions reporting
	Mapping seasonal land cover dynamics using SAR data
Improving data access	High resolution DEM (TanDEM-X or 30 m SRTM)
	Ensure on-going access to Landsat-like data, or alternative data sources/methods that comply with existing programs
Institutional frameworks	Set-up and design of NFMS and NFI
	Open source software
	Cloud computing opportunities
	Capacity enhancement

Annex C.1 NFMS Set-up/Continuous Improvement

(i) Data access

The Space Data Coordination Group (SDCG) for GFOI will continue to support participating countries by further developing the CEOS Data Strategy (refer to Section 2.2) for coordinated, sustainable global data acquisition based on a number of core satellite missions from which data will be freely available to support NFMS and REDD+ involvement. The core missions include Landsat-7/-8, Sentinel-1/-2, CBERS-4 and RADARSAT Constellation Mission (RCM). Data acquisition in a range of modes will largely fulfil the requirements for annual/biennial wall-to-wall forest monitoring (medium resolution) and semi-annual warning systems (coarse resolution). GFOI will also liaise with commercial non-core (e.g., RapidEye, TerraSAR-X) mission providers in support of GFOI priority R&D activities. Access to very high resolution (VHR) data for validation and high resolution DEMs (e.g., TanDEM-X) fall into this category.

(ii) Institutional frameworks

NFMS Issue

Building in-country capacity to develop and maintain an MRV/NFMS for REDD+ reporting is desirable by many countries. Following on from GEO-FCT capacity building, GFOI wishes to provide on-going support to participating countries in the initial phase of NFMS system design, from conceptual frameworks to operations, advising on NFI, spatial data infrastructure and facilitating training in image processing. This idea is suggested in collaboration with the FAO, as they are actively engaged in system set-up, software development and training for forest and land use change assessment in developing countries.

Sophisticated software is required to process suitably calibrated, time-series satellite imagery for extraction of forest cover and change information. Licensing costs of commercial software for processing EO data are often prohibitive to developing countries. Open source does exist but not always in a user-friendly format. To an inexperienced user, the processing requirements and sequence of steps required to produce a calibrated image suitable for extraction of forest cover information may be poorly understood. The development of technical guidance and an open source software toolkit for streamlined processing of EO data, particularly radar, would greatly improve the capacity of countries to process and integrate a range of data for forest monitoring and carbon stock assessment. Cloud computing opportunities would also allow users to share online computational power and expertise between developed and developing countries.

Remote Sensing Considerations

Open-source software for processing EO data exists but installation can be complicated, code may have to be manipulated, and command line interfaces may be confusing to the non-initiated. Commercial software often provides streamlined and batch processing capability, but at a cost which may be limiting to developing countries. Agencies like INPE have developed their own software for visualisation and manipulation of remote sensing data and within a multi-user, interactive framework. Users are reliant on the supply of suitably calibrated data for analysis however.

Wide-area forest monitoring requires mosaicking of tens to hundreds of suitably geometrically and radiometrically calibrated images, which is no easy task. Advanced atmospheric, bi-directional reflectance distribution function (BRDF), and terrain correction procedures are required for calibration of optical data. Speckle filtering and compensation for terrain effects and shadowing is required for SAR data. WHRC developed their own open source based toolkit for processing calibrated multi-source satellite mosaics. The availability of post-processing routines, e.g., segmentation, would assist countries with limited expertise. Segmentation routines optimised for SAR and the particular forest ecosystem are also desirable.

Technology Transfer/Capacity Building

To increase country capability in MRV and REDD reporting, it is suggested that GFOI, in collaboration with FAO, support the following activities:

i. On-going technical and administrative support for design and set-up of a national REDD+ program (including EO-based NFMS and NFI).

ii. Document available open source software for processing optical and SAR data - identify gaps.

iii. The development of a software toolkit for geometric and radiometric correction of multi-source data, reliant on open source code bundled in a user friendly GUI.

iv. Investigate cloud computing opportunities to increase processing capacity and data storage, and facilitate technology transfer and inter-agency collaboration.

v. Develop in-country capacity to perform remote sensing data processing, interpretation and monitoring through targeted capacity building workshops.

Annex C.2 General Method Improvement

(i) Time-series consistency: Cloud-free compositing

NFMS Issue

The IPCC Guidelines emphasise the need for time-series consistency of monitoring in order to monitor changes in a credible, good practice, manner. Recent availability of extensive archives of medium resolution optical data (e.g., Landsat) provides a good opportunity to assess longer term forest and land cover change. Cloud-free imagery can be very difficult to obtain in sub/tropical regions due to persistent cloud cover. As a result, there are gaps in the data record, and the reliability of, for example, deforestation estimates is poor [45]. Pixel-mining and image compositing approaches using multi-temporal and/or multi-scale data are required to produce the consistent cloud-free time-series suitable for monitoring deforestation and land cover change.

Remote Sensing Considerations

Cloud and cloud shadow are potential sources of error in land cover analyses. This is particularly relevant in tropical areas due to persistent cloud cover. It is often difficult to obtain useable (e.g., <10 % cloud cover) cloud-free optical data for mosaicking over large regions. Cloud-screening is often implemented, whereby clouds and/or cloud shadow pixels are identified and flagged in an output mask. Mosaicking cloud-free sections of images presents the simplest approach. Alternatively, pixel-mining or satellite image compositing is applied, whereby contaminated pixels are identified and the reflectance values replaced using cloud-free data from the compositing period, so reconstructing cloud-free imagery [214]; [215]; [216]. Alternative gap-filling approaches also exist whereby reflectance values are estimated using coarser or higher spatial resolution data (e.g., substituting cloud-affected Landsat pixels with downscaled MODIS data).Sensors like MODIS and future Sentinel-2 have a higher observation frequency compared to other medium resolution sensors, e.g., Landsat, so increasing the opportunities for cloud-free observations. MODIS being coarser resolution however, is inadequate for accurate estimates of deforestation at sub-pixel scale [45], and gap-filling using these images may be inadequate for detecting subtle change.

Technology Transfer/Capacity Building

Some countries have the technology and capacity to produce cloud-free composites as part of the processing chain. Other countries may require technical advice on:

i. Pixel-mining or compositing approaches that estimate missing reflectance values, based on the time-series, to produce complete coverages.

ii. Gap-filling/integration of multi-scale satellite data to produce complete coverages.

iii. Assessment of the accuracy of derived forest cover, land use and change estimates using composite datasets.

(ii) Time-series approach

NFMS Issue

Time-series processing of remote sensing data provides the basis for consistent estimation of forest cover and change. Recent developments in the availability of medium resolution remote sensing data (e.g., Landsat) and processing power provide an opportunity to improve the accuracy and reliability of the results as well as possibly providing more information on disturbances and regrowth. Two approaches are utilised: (i) spatio-temporal data mining or knowledge based information extraction, and (ii) following trajectories at the same phenological stage through time. These methods need to be assessed and operationalised with respect to producing quantifiable estimates of forest cover change. Studies have also shown that using dense time-series SAR data, particularly at C-band, is key to enhancing information extraction.

Remote Sensing Considerations

Recent research effort has been channelled into the development of hyper-temporal processing routines to better exploit available time-series optical data for forest area change mapping and a host of other applications. With the opening up of the Landsat archive, countries have complete access to historic medium resolution data for longer-term forest monitoring and carbon stock estimation, but not necessarily the methods or capacity to do so. Efficient methods are required to ingest the large data volumes, and consistently produce reliable estimates of forest or land cover change, taking into account seasonal variations, climatic influences, disturbance from fire etc.

Data mining is one such technique to produce quantifiable estimates of forest cover change. Practical methods are required to ingest the large volumes of satellite data into mining software and extract pixel-level information of relevance to forest change. To address the challenge of intelligent information extraction relating to forest cover change, mining methods need to be cognizant of climate and ecosystem characteristics such as seasonality, inter-region variability, multi-scale features, spatio-temporal autocorrelation, high dimensionality, high data volume and data quality issues [213]. Ideally, data mining approaches will lead to automated means of identifying and characterising the relationships between change and anthropogenic or other activity. A recent approach employs multi-year pixel/segment trajectories that evaluate changes in biomass or canopy cover by separating 'noise' (commission error) from actual change using trend information. Disturbance and regrowth can be assessed via analysis of stable and change pixels, and in so doing, use the 'life history' of the pixel to detect change. A baseline or reference condition against which to evaluate the change is required, and may be derived from plot level biomass data.

Studies have shown that dense time-series SAR data is key to enhancing information extraction over forested areas. In particular, dense time-series C-band SAR measurements are critical for characterisation of the statistical variability and seasonal variation of backscatter over forests. Multi-temporal averaging (which reduces speckle noise) and other change detection techniques applied to SAR images acquired under similar viewing geometry are useful for detecting deforestation and other LULCC activity. Further methods development is required on how to exploit dense time-series SAR data for deforestation monitoring, including the simulation of Sentinel-1A/B and RCM datasets.

Technology Transfer/Capacity Building

Some countries have the technology and capacity for time-series processing for consistent estimation of forest cover and change. Other countries require technical advice on:

i. Appropriate spatio-temporal data mining techniques for intelligent information extraction relating to forest or land use change. Methods of identifying and characterising change and understanding the relationships between the type and magnitude of changes and anthropogenic variables are required.

ii. Pixel or segment based trajectory methods that use the weight of the time-series to detect forest or land use change, associated accuracy metrics, and development of rigorous methods for assessing uncertainty, which, to date, have not been reported. May involve fine-tuning of forest transition probabilities, and integration into an automated processing chain.

iii. Multi-temporal averaging and other change detection techniques to optimise information extraction from dense time-series C-band SAR data.

iv. Evaluation of limitations of time-series approaches, e.g., when input data are poorly geometrically and/or radiometrically calibrated, or collected under different viewing conditions (seasonal sun-sensor-target viewing geometry).

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Annex E Acronyms used in R&D Document

AGB	Above Ground Biomass
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ALOS	Advanced Land Observing Satellite (Japan)
AVNIR-2	Advanced Visible and Near Infrared Radiometer type 2 (Japan)
C	Carbon
CBERS	China-Brazil Earth Resources Satellite series
CEOS	Committee on Earth Observation Satellites
CONAE	Comisíon Nacional de Actividades Espaciales (Argentine Space Agency)
CORINE	Coordination of information on the environment (European Commission)
DEM	Digital Elevation Model
DMC	Disaster Monitoring Constellation
FAO	United Nations Food and Agriculture Organisation
FCT	Forest Carbon Tracking
FullCAM	Full Carbon Accounting Model
GEO	Group on Earth Observations
GFOI	Global Forest Observations Initiative
GHG	Greenhouse Gas
GLAS	Geoscience Laser Altimeter System (USA)
GOFC-GOLD	Global Observation of Forest Cover – Global Observation of Land Dynamics
ICESat	Ice, Cloud and land Elevation satellite (USA)
INPE	Instituto Nacional de Pedquisas Espaciais (Brazilian National Institute for Space Research)
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing satellite series
JAXA	Japan Aerospace Exploration Agency
JERS	Japan Earth Resources Satellite
LiDAR	LIght Detection And Ranging
LULC	Land Use, Land Cover
LULCC	Land Use, Land Cover and Change
MODIS	Moderate Resolution Imaging Spectroradiometer (USA)
MRV	Measurement, Reporting and Verification
NDs	(GEO FCT) National Demonstrator countries
NFI	National Forest Inventory

NFMS	National Forest Monitoring System
NovaSAR	S-band SAR satellite (U.K.)
PALSAR	Phased Array L-band Synthetic Aperture Radar (Japan)
RADARSAT	C-band SAR satellite series (Canada)
RCM	RADARSAT Constellation Mission (Canada)
REDD+	Reducing Emissions from Deforestation and Forest Degradation, conservation, sustainable management of forests and enhancement of forest carbon stocks
SAR	Synthetic Aperture Radar
SAOCOM	Satélite Argentino de Observación Con Microondas (Argentine Microwaves Observation Satellite)
SDCG	CEOS Space Data Coordination Group
SPOT	Satellite Pour l'Observation de la Terre (France)
SRTM	Shuttle Radar Topography Mission
TanDEM-X	Second TerraSAR-X satellite for Digital Elevation Measurement (Germany)
TerraSAR-X	X-band SAR satellite (Germany)
UKSA	U.K. Space Agency
UNFCCC	United Nations Framework Convention on Climate Change
UN-REDD	United Nations collaborative initiative on Reducing Emissions from Deforestation and Forest Degradation (REDD)
VHR	Very High Resolution
WHRC	Woods Hole Research Centre