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Review of literature on monitoring to support REDD

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The UN-REDD Programme, implemented by FAO, UNDP and UNEP, has two components: (i) assisting developing countries prepare and implement national REDD strategies and mechanisms; (ii) supporting the development of normative solutions and standardized approaches based on sound science for a REDD instrument linked with the UNFCCC. The programme helps empower countries to manage their REDD processes and will facilitate access to financial and technical assistance tailored to the specific needs of the countries.

The application of UNDP, UNEP and FAO rights-based and participatory approaches will also help ensure the rights of indigenous and forest-dwelling people are protected and the active involvement of local communities and relevant stakeholders and institutions in the design and implementation of REDD plans.

The programme is implemented through the UN Joint Programmes modalities, enabling rapid initiation of programme implementation and channeling of funds for REDD efforts, building on the in-country presence of UN agencies as a crucial support structure for countries. The UN-REDD Programme encourage coordinated and collaborative UN support to countries, thus maximizing efficiencies and effectiveness of the organizations' collective input, consistent with the "One UN" approach advocated by UN members.

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1. Introduction

This literature review looked at 138 peer-reviewed journal articles and 35 reports and other papers on the issue of monitoring carbon emissions and sinks to support REDD. Section 2 provides an overview about the distribution of subjects and scopes of the REDD literature related to monitoring. Section 3 discusses an overview of available methodologies and datasets with reference to key papers from a vast pool of literature. References for all articles and reports are given in the final section. It should be noted that although best efforts were made to collect all publications related to REDD and monitoring, the bibliography is by no means complete.

2. Literature matrix

The following table summarizes the literature review. The rows list four major subjects related to REDD and monitoring: baseline setting, monitoring of deforestation, monitoring of forest degradation, and broader monitoring which refers to discussions to provide knowledge and feedback on co-benefits, drivers, trade-offs and linkages to social and environmental issues. The columns contain three spatial scales (pilot/case studies, national, or regional/global) and two methodologies (field sampling/surveys or remote sensing). The statistics are for journal articles only but the same pattern holds true for the reports except for a skew towards pilot/case studies and national scale.

Table 1 Summary of subjects, scales and methodologies found in 138 peer-reviewed articles on REDD related to monitoring

% of articles	pilot/case	national	regional/global	field sampling/survey	remote sensing
baseline	14	12	32	9	21
monitoring deforestation	16	14	20	7	20
monitoring degradation	11	6	9	9	14
broader monitoring	3	8	4	0	0

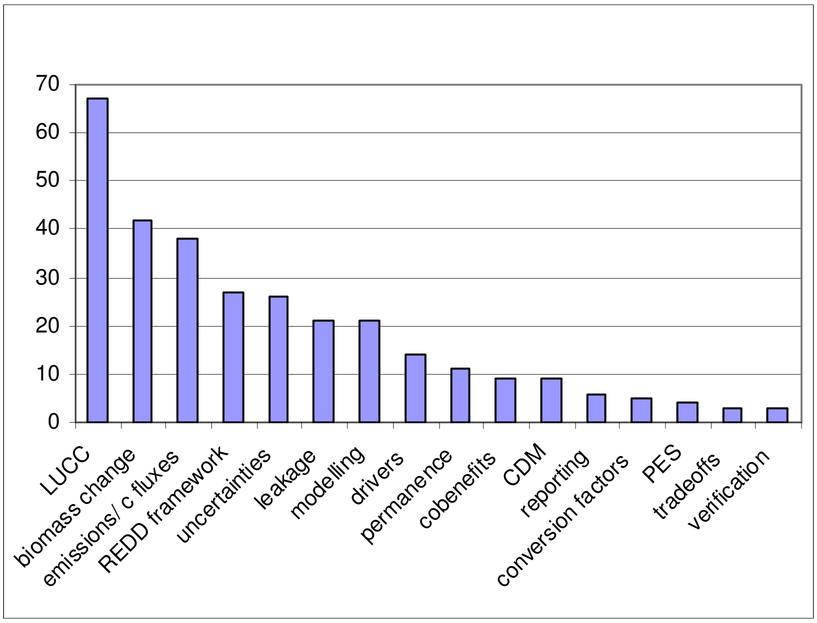
* One paper is allowed to be categorized into multiple cells, so the total for each row/column does not add up to 100%.

32% of the papers discussed baseline emissions at regional to global scale, mainly in the tropics and the Amazon. Many of the papers are from remote sensing research. 21% of the papers discussed baseline setting and remote sensing, 20% deforestation monitoring and remote sensing. Few papers discuss forest degradation (15% or less for all categories under degradation), even fewer broader monitoring.

Of the analyzed papers, 52% are technical papers, 35% review papers, and 17% policy papers (some papers are counted multiple times).

Keywords were assigned to each paper. Most frequent ones are land use and land cover change (LUCC), carbon fluxes and biomass change, followed by REDD policy framework. Papers on payment for ecosystem services (PES), tradeoffs and verification are very scarce.

Figure 1 Counts of keywords found in 138 peer-reviewed articles on REDD related to monitoring



Most of the papers reviewed here were published in the last 10 years. The analysis indicates that research for that period focused on development of remote sensing techniques. Methodologies on how to link field inventories and remote sensing are one of the major knowledge gaps.

Most resources have been spared for measuring area of deforestation. There is a need for advancing research on measurement of carbon stock in forests and emission estimates from avoided deforestation and forest degradation.

Most published research did not deal with national-scale monitoring of forests. As negotiations for post-2012 framework move forward, “broader monitoring” that bridges technical monitoring capacities and REDD policy formulation at country level will become more important than ever. Contributions from the research community to support the REDD process are anticipated.

3. Overview of literature on monitoring for REDD

IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (GPG-LULUCF, 2003), IPCC Guidelines for National Greenhouse Gas Inventories for Agriculture, Forestry and Other Land Uses (GL-AFOLU, 2006) and GOFC-GOLD Sourcebook (2008) provide good guidance on methods for REDD monitoring and verification. There is a special issue on tropical deforestation and greenhouse gas emissions in an open-access journal Environmental Research Letters (http://www.iop.org/EJ/toc/1748-9326/2/4) with a few review papers in the context of REDD (Gibbs and Herold, 2007; Achard et al., 2007; Gibbs et al., 2007; Mollicone et al., 2007; Herold and Johns, 2007). This literature review does not try to reiterate these good resources. Instead, the current capability of monitoring is reviewed with specific reference to key papers for interested readers.

3.1 Historical trends of deforestation and forest degradation

Emissions from forest cover changes can be estimated from: 1) area of deforestation, 2) initial carbon stocks for the base period, and 3) changes in the carbon stocks caused by deforestation and degradation (Achard et al., 2007; Houghton, 2005; Ramankutty et al., 2007).

Historical changes in deforestation area may be derived from FAO Forest Resources Assessment statistics. According to the GOFC-GOLD Sourcebook (2008), from remote sensing imagery it is possible to estimate forest area change with confidence from 1990s onwards. Achard et al. (2007) lists a number of global land cover maps from remote sensing (coarse spatial resolution, 1 km to 300 m). They may be too coarse for primary use at national level but can be used to detect major deforestation areas and provide consistency check with more costly mid-resolution estimates (10 - 50 m). Limitations are resources and data availability, rather than methodologies. There are only a few years (1975, 1990 and 2000, Landsat) for which global mid-resolution satellite imageries for estimating forest cover are available (Mollicone et al., 2007).

Different methods for estimating deforestation rates at regional and global scales using coarse-resolution remote sensing data such as those from the NOAA-AVHRR are described in Mayaux et al. (2005). However for REDD baseline setting most appropriate dataset is from mid-resolution (Landsat). Landsat imagery is preferred for moderate cost and acquisition policy, easy availability through the Internet and a suitable resolution for the detection of changes in canopy condition, extent and land use around forest areas (Fuller 2006). In response to wide availability of satellite imagery, a number of change detection techniques have been developed (see review from Lu et al., 2003; Coppin et al., 2004).

Two basic approaches of estimation methods are generally proposed: sampling and wall-to-wall assessment with remote sensing imageries. Beyond these approaches there are discussions of projecting historical deforestation rate into the future to establish baselines for the commitment period of REDD. For example, Brown et al. (2007) compares three models of different sophistication: a non-spatial analytical model of forest area change, a non-spatial simulation of land-use carbon sequestration, and a geographical modeling of forest area using spatial regression. Major drivers of historical deforestation have to be identified to run the models.

Historical estimates of forest carbon stocks can be estimated from a variety of sources and literature, complemented by field measurements (Brown et al., 2007). Historical estimate of forest degradation may not be possible to quantify (Mollicone et al., 2007) due to lack of sufficient data.

3.2 Monitoring deforestation

The issue of monitoring emissions from deforestation is two folds: estimation of deforestation area and associated carbon stock.

Deforestation area

The most practicable approach for monitoring deforested area at national level is through satellite imagery with support by ground based observations. De Fries et al. (2007) propose three methods: 1) visual interpretation of aerial photos or satellite imagery, 2) wall-to-wall mapping over the forest area with satellite imagery, and 3) hot-spot analysis. The choice of method depends on cost for data acquisition, technical capacities, size and patterns of deforestation, seasonality of forest, size of country and forest area. For more cost efficient analysis than wall-to-wall approach, several sampling approaches are preferred: 1) expert knowledge identifying areas of rapid deforestation, 2) nested approach with medium resolution data, and 3) statistical sampling capturing patterns of deforestation.

Brazil's PRODES and DETER programs are based on a combination of medium and high resolution data suing a mixture model approach to identify changes in fraction of bare soil and vegetation (De Fries et al., 2005). No single method can be applied in all situations of deforestation monitoring. A variety of automated approaches to analyze large volumes of data have been developed. The appropriate method and data source depend on the type of forest, deforestation process, size of clearings, and sensor for monitoring (De Fries et al. 2005). Table 2 summarizes optical sensors with different resolutions for deforestation monitoring.

Table 2 Optical sensors of different spatial resolution for monitoring (adapted from De Fries et al., 2007)

Sensor resolution	Examples of current sensors	Minimum mapping unit (change)	Cost	Utility for monitoring
Coarse (250-1000 m)	SPOT-VGT (1998-), Terra-MODIS, Envisat-MERIS (2004-)	~100 ha, ~10-20 ha	Low or free	Consistent pan-tropical annual monitoring to identify land clearings and locate hotspots for further analysis with mid resolution
Medium (10-60 m)	Landsat TM or ETM+, SPOT HRV, Terra-Aster, AWiFs LISS II, CBERS HRCCD, DMC	0.5-5 ha	Landsat and CBERS free from 2009, historical: <$0.001/km^2, recent data: $0.02-0.5/km^2	Primary tool to map deforestation and estimate area change
High (<5 m)	IKONOS, Quickbird, Aerial photos	< 0.1 ha	High to very high $2-30/km^2	Validation of results from coarser resolution analysis, training of algorithms

For more information on global land cover maps using coarse resolution optical sensors, Achard et al. (2007) provides a good summary (Table 3). Coarse-resolution system such as AVHRR, MODIS and SPOT-VGT can obtain enough cloud-free views at monthly-to-annual intervals (Fuller 2006).

Table 3. Coarse resolution global land cover maps for monitoring deforestation (adapted from Achard et al., 2007)

Product	Resolution	Sensor
MODLAND	Global 1 km	TERRA MODIS
GLC-2000	Global 1 km	SPOT-VGT
-	Global 500 m	TERRA MODIS
GLOBCOVER	Global 300 m	Envisat MERIS

In order to reduce costs and time for area-extensive analysis, effective use of mid-resolution satellite images may be practical and will be a primary data source for REDD monitoring. Table 4 presents a summary of mid-resolution sensors (Achard et al., 2007). NASA and USGS have been working to compose imagery for a mid-decadal (around 2005/2006) dataset from Landsat-5 TM and Landsat-7 ETM+.

Fine-resolution multi-spectral commercial systems such as IKONOS and Quickbird may not satisfy REDD routine monitoring requirements because of their low temporal resolution and relatively small-area coverage but still provide a source for verification of forest maps from coarse to mid- resolution imagery (Fuller 2006).

Table 4 Availability of mid-resolution sensors (adapted from Achard et al., 2007)

Nation	Sensors	Resolution
US	Landsat-5 TM (optical)	30 m
US	Landsat-7 ETM+ (optical)	30 m
US/Japan	Terra ASTER (optical)	15 m
India	IRS-P2 LISS-III and AWIFS (optical)	23 and 56 m
China/Brazil	CBERS-2 HRCCD (optical)	20 m
UK, Turkey, Algeria	DMC (optical)	30 m
France	SPOT-5 HRV (optical)	5-20 m
Japan	ALOS PALSAR (radar)	50 m

Other types of sensors are potentially useful particularly to overcome major limitations of optical sensors in persistently cloudy parts of the tropics (De Fries et al., 2007; Achard et al., 2007). The capabilities of radar such as ERS1/2 SAR, JERS-1, ENVISAT-ASAR and ALOS PALSAR have been demonstrated by several pilot studies. Lidar does not provide global coverage but delivers information on the vertical structure of the forest.

The complementary role of ground observations to remote sensing estimates is often stressed (De Fries et al., 2007). The appropriate scale of ground-truthing depends on national circumstances and individual projects. Although written for CDM projects, Winrock

(2005b) is an additional resource to IPCC GPG-LULUCF (2003) that provides guidance for field measurements.

Carbon stock

IPCC GPG-LULUCF (2003) and GL-AFOLU (2006) compiled methods for determining changes in carbon stocks for estimating GHG emissions from deforestation. According to De Fries et al. (2007) there are no standard methodologies for measuring biomass through remote sensing at national scale. Various pilot studies use airborne Lidar data, radar observations, and high resolution optical data to estimate biomass of different forest types but they are costly and not ready for operational use.

Houghton et al. (2001) compared seven biomass estimation methods (three field measurements, two methods that use relationship to climatic variables, and two remote sensing methods) for application in the Brazilian Amazon. More direct measurements of aboveground biomass with remote sensors such as radar and optical sensors are being studied; however, most of them are not mature enough for operational use. An exhaustive list of available methods to estimate national level forest carbon stocks is available in Gibbs et al. (2007) and it is reproduced here as Table 5. For benefits and limitations of each method see Gibbs et al. (2007).

Current capabilities for most developing countries are limited to compilations of point-based biomass harvest measurement data, literature on carbon stocks (national inventories, FAO FRA forest inventory data) and default data in GPG-LULUCF (2003). Biome averages are currently the only source of globally consistent forest carbon information. Ground-based forest inventory would significantly improve estimates of carbon stock (Gibbs et al. 2007).

Table 5 Methods for carbon stock estimates (adapted from Gibbs et al., 2007)

Method	Description	Uncertainty
Biome averages	Estimates of average forest carbon stocks for broad forest categories based on a variety of input data sources	High
Forest inventory	Relates ground-based measurements of tree diameters or volume to forest carbon stocks using allometric relationships	Low
Coarse to mid resolution optical remote sensors such as Landsat and MODIS	Uses visible and infrared wavelengths to measure spectral indices and correlate to ground-based forest carbon measurements	High
High-resolution airborne optical remote sensors such as aerial photos and 3D digital aerial imagery	Uses satellite images to measure tree height and crown area and allometry to estimate carbon stocks	Low to medium
Radar remote sensors such as ALOS PALSAR, ERS-1, JERS-1, Envisat	Uses microwave or radar signal to measure forest vertical structure	Medium
Laser remote sensors	Lidar uses laser light to estimate forest height and vertical structures	Low to medium

3.3 Monitoring forest degradation

The estimation of emissions from forest degradation requires determining the area and type of degradation as well as changes in carbon stocks.

Degradation area

Monitoring of forest degradation with remote sensing is more challenging and not yet as well established as monitoring of deforestation (De Fries et al 2007). Differences in reflectance among degraded forests and several intact, carbon-richer forest types with more open canopies are very subtle and both types can be easily confused when a detailed vegetation map of natural canopy types is not available (Olander et al. 2008). However, the subject is evolving quickly; UNFCCC will establish a special working group on methodological issues of degradation and several organizations (e.g. FAO) and initiatives (e.g. UN-REDD) will intensify their efforts on this topic.

Current attempts to monitor degradation with remote sensing focus on selective logging and forest fires. Many other forms of forest degradation, like overgrazing and unsustainable extraction of non wood forest products, have been considered as almost undetectable (Peres et al. 2006). A reliable identification of all major types of forest degradation will probably require innovative methods coupling satellite imagery with ground-based observations (Gibbs et al. 2007).

For the purpose of national monitoring in the REDD context, in many parts of the world remotely sensed data is likely to be the primary practical option to monitor areas of forest degradation. Accuracy assessments using field data or a sample of higher quality data should be part of every national monitoring system (e.g. Lowell, 2001; Wulder et al, 2006).

The choice of the optical sensor depends on the degradation intensity, the extent of the area and the technique (visual interpretation or automated image processing) (GOFC-GOLD Sourcebook 2008). Radar data have potential but requires more research (De Fries et al., 2007).

Coarse resolution images, like MODIS, have been used to map fire-affected areas at the regional scale (e.g. Roy et al. 2005b, Morton et al. 2008). Such data have a high temporal frequency but cannot detect a large part of small-scale forest degradation. Mid-resolution sensors, such as Landsat and SPOT, have been applied to map selective logged and burned forest in some regions, in particular the Amazon (e.g., Souza & Barreto, 2000; Asner et al., 2005). Often, spatial patterns of log landings and other logging related infrastructure are considered to indirectly derive the affected area or improve estimates from gap detection (e.g. Souza et al., 2005; Souza & Barreto, 2000).

However, these coarse to mid-resolution sensors do not deliver information about forest structure and composition and have difficulties to distinguish old degraded forest (>2 years) from intact forests (Souza & Roberts 2005). Ideally, time series of cloud-free images would be needed, at least once a year or even more, to distinguish degradation from effects of seasonality (Olander et al. 2008), to differentiate fire types and account for repeated degradation events. However, such Landsat time series are usually not available (Asner 2001).

High resolution data are necessary in order to identify forest degradation in sufficient detail. A few studies with high resolution sensors (Ikonos, Quickbird) have been conducted. However, wider application is limited by high costs for image acquisition, small coverage, demanding processing and frequent cloud cover in the humid tropics (Olander et al. 2008).

In large areas with low intensity degradation, indirect methods are preferred, like a simple categorization into intact and non-intact forests based on topographic maps and GIS data showing infrastructure etc. and a fine-shaping of boundaries via visual interpretation of Landsat data or high resolution sensors (GOFC-GOLD Sourcebook 2008). Such a simple approach would allow accounting for carbon losses from forest degradation in the IPCC guidelines, reporting this as a conversion of intact to non-intact forest.

A large number of global fire observing systems and data products (~1 km resolution) have been developed (see Global Fire Monitoring Center http://www.fire.uni-freiburg.de) including a global wildlife fire assessment by FAO, active fire and burnt area satellite products by EC JRC, NASA, EUMETSAT, NOAA, and ESA. Multi-year burned area products, based on coarse resolution satellite data, are about to be released (MODIS, L3JRC, GLOBCARBON) (GOFC-GOLD Sourcebook 2008).

At national level, pilot activities and systems for fire-monitoring are emerging including pre-fire, active fire and post-fire assessments (GOFC-GOLD Sourcebook 2008) (see Table 6). Operational fire early warning systems were developed for Indonesia and Malaysia based on the Canadian Forest Fire Danger Rating System (de Groot et al. 2007).

Table 6. Fire observations and their usefulness for national REDD implementation (adapted from GOFC-GOLD Sourcebook, 2008)

Approach	Information	REDD objective	Suitability	Limitations
Pre-fire	early warning systems	protect areas at risk	mostly for countries with significant amount of wildland fires and known fire regimes	-
Active fire	hotspot satellite data	fire relief and active emission reductions	mostly for countries with large number of small-scale deforestation fires	information on land use/land cover essential to exclude agricultural burning and hotspots from volcanoes and gas flares, underestimation due to clouds
Post-fire	burned area estimates	support estimation of areas of deforestation and degradation	all countries with forest loss due to fire	data intensive; misses smaller and multiple burns, improves in combination with active fire data

Carbon stocks

Accounting for differences in the forest carbon stocks as a result of degradation and recovery from clearing is important for estimating carbon emissions (Gibbs et al. 2007). Secondary re-growth of deforestation may be a considerable factor in some areas but is difficult to monitor (Persson & Azar 2007).

Main changes in carbon stocks due to forest degradation occur in the vegetation. Generally, soil carbon emissions related to selective logging of timber or fuel wood are insignificant but can be considerably on peatland when associated with drainage and fires (GOFC-GOLD Sourcebook 2008).

GL-AFOLU (2006) recommends depending on the available data two methods for estimating annual carbon change in the class "Forests remaining forests". The stock-difference method compares carbon stocks before and after degradation (e.g. fire), while the gain-loss method accounts for biomass gains (e.g. tree growth after logging) and losses (e.g. timber harvest). More details about the methods can be found in GL-AFOLU (2006) and GOFC-GOLD Sourcebook (2008).

Gibbs et al. 2007 suggest a comprehensive approach to measure forest carbon under different forest conditions using a stratification matrix based on forest type and condition (e.g. mature, logged, secondary, burnt) to capture the major variation in forest carbon stocks. Emissions can then be quantified by comparing estimates for carbon storage under different forest conditions. A major constraint with the approach is to map all forest types with different forest conditions over an entire country, which is not possible with current remote sensing technology.

Case studies which combine remote sensing and field sampling to estimate changes in carbon stock and emissions from forest degradation were conducted, for example, in the Amazon (Treves et al. 2004, Saatchie et al. 2007) and Indonesia (Page et al. 2002). Detailed field studies on changes in carbon stocks due to selective logging exist only locally (e.g. Feldpausch et al. 2005) but are not applicable to larger temporal and spatial scales.

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MRV Working Paper series

WP Nr.	Title	Date
01	*Role of satellite remote sensing in REDD by Peter Holmgren*	13 October 2008
02	*REDD-Workshop Monitoring, Assessment and Verification (report of the Washington meeting)*	16-17 September 2008
03	*Review of literature on monitoring to support REDD by Claudia Hiepe, Hideki Kanamaru*	16-17 September 2008